NEURAL MODULATION OF ISOMETRIC CONTRACTIONS

By

JULIE A. ROBICHAUD

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By

Julie A. Robichaud

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Chair: L. Keith Tennant
Cochair: Denis Brunt
Major Department: Exercise and Sport Sciences

The dual-strategy hypothesis was developed to explain how single-joint voluntary movements were controlled. Movements were divided into two different strategies which were suggested to be modulated by different excitation pulses. Changes in the H-reflex prior to the movement may be one way to evaluate the existence of this excitation pulse. This study was designed to test the existence of the excitation pulse by quantifying changes in spinal excitability that may occur with changes in bandwidth and force level during a ballistic ankle plantar flexion isometric contraction. Eleven participants were tested and each was seated in a modified chair with their hips at 90°, knees at 120°, and the ankles neutral. A force transducer was placed to measure ankle force output. Following a visual stimulus subjects were trained to produce a plantar flexion force of 25% and 50% of a maximum voluntary contraction, within bandwidths of 5% and 15% of the selected force level. Soleus motor neuron reflex excitability was analyzed measuring changes in the H/M ratio. The H-reflex was randomly elicited at intervals of 50, 75, 100, 150, and 175 ms following the visual stimulus. A two-way repeated-measures analysis of variance indicated a significant effect among bandwidths for the time of change in spinal excitability ($\underline{F}_{1,10} = 21.2$; $\underline{p} \leq .01$) (5% bandwidth 56 ms and 15% bandwidth 33 ms), slope of facilitation ($\underline{F}_{1,10} = 25.4$; $\underline{p} \leq .01$) (5% bandwidth 10.5% change of H/M ratio/sec, 15% bandwidth = 20.4% change of H/M ratio/sec) and peak facilitation ($\underline{F}_{1,10} = 8.6$; $\underline{p} \leq .01$) (5% bandwidth = .669 H/M ratio, 15% bandwidth = .758 H/M ratio). There was no difference between force level and any measure of spinal excitability. These results indicate that changes in bandwidth can influence time, slope, and peak of facilitation. However, force level does not affect any of these measures. Results support the existence of two different excitation pulses which appear to be regulated by the accuracy of the movement. Implications of this finding to the control of voluntary movement will be evaluated.

CHAPTER 1
INTRODUCTION

Individuals perform hundreds of voluntary single and multijoint movements during the course of a single day. When observing these movements, there is enormous diversity. There are a number of factors, including the angle of movement, number of joints involved in the movement, body position of the individual, and environmental factors (i.e., wind, rain, ect.), which can influence how a movement is performed. Nonetheless, these movements seem to produce some commonalties, which may be regarded as movement regularities. The neurophysiological and musculoskeletal mechanisms involved with multi- and single-joint voluntary movements may be difficult to understand. The underlying mechanisms (neurological and musculoskeletal), which may control these regularities of voluntary single-joint movement have been investigated through, using a variety of experimental methods (Ghez & Gordon, 1987; Gottlieb, Corcos, & Agarwall, 1989a; Schmidt, 1979). When multi- and single-joint movements are understood in healthy individuals, this may lead to a better understanding of movement dysfunction in patient populations.

Movement dysfunction in patient populations such as those who have Parkinson disease or have sustained a stroke is not well understood. The most appropriate method to use for motor relearning or rehabilitation is difficult to asses unless researchers are able to identify the precise nature of the dysfunctions that produce cognitive, programming, or execution deficits. The analysis of movement dysfunction in patients would be facilitated if there were a comprehensive model for single-joint control. This may enhance the practitioner's ability to identify which patients have cognitive, programming, or execution deficits that impede the desired movement. A model, that encompasses both programming and execution components of movement, would provide a more fundamental basis for the understanding of movement dysfunction. Therefore, therapists' abilities to focus treatments on the actual movement deficits might be enhanced.

A model of single-joint control, the dual-strategy hypothesis, has been recently developed by Gottlieb, Corcos, and Agarwall (1989a). Supportive research has established that predetermined movement strategies can be differentiated according to specific electromyographic (EMG) activity and torque trajectories and may be divided into speed sensitive (SS) and speed insensitive (SI) strategies. The SS strategy is adopted when the speed of the movement is implicitly or explicitly controlled. In the SI strategy, there is no intention or requirement to control movement speed. This model of single-joint control has been deemed a satisfactory explanation of isotonic movements; however, ambiguity still exists as to whether isometric contractions may be appropriately classified using this model.

The utilization of the SS or SI strategy is based upon different excitation pulses with the same initial pulse determining both force trajectories and EMG activity. The SS and SI strategies should elicit different excitation pulses. These excitation pulses may be represented by changes in spinal cord excitability prior to movement onset, with the different strategies producing different excitation pulse patterns (Gottlieb, Corcos, & Agarwall, 1989a). The SS strategy should modulate the excitation pulse height, while the SI strategy may alter the width of the excitation pulse. Although Gottlieb et al. (1989a) outlined specific relationships between torque trajectories and agonist EMG activity with different movement strategies, there was no attempt to evaluate the existence of the excitation pulse or to show relationships between this pulse and motor programming.

Evidence suggests different excitation pulse patterns may be reflected by different patterns of movement. For example, in an anticipation timing task, which could be classified as an SI strategy, Frank's (1976) data showed an increase in the time period of motor neuron excitability. This would be classified as pulse width modulation. Eichenberger and Ruegg (1984) ascertained that faster reaction times were associated with higher levels of motor neuron excitability that would be classified as pulse height modulation. In this study, an attempt will be made to analyze the relationships between torque trajectories and agonist EMG activity of single-joint isometric movements. Additionally, the proposed excitation pulse will be evaluated by measuring changes in spinal excitability prior to movement onset during voluntary isometric movements.

Single-Joint Movements

Woodworth (1899) was one of the first researchers to analyze single-joint voluntary movement. Woodworth indicated that two phases of movement controlled voluntary single-joint limb movements. Since Woodworth's original research, many investigators have analyzed various combinations of limb trajectory, EMG amplitude and duration, movement time, acceleration, and peak velocity data while attempting to determine the existence of strategies for performing single-joint movements (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Corcos, & Agarwall, 1989a, 1989b; Fitts, 1954; Gordon, & Ghez, 1987a; Schmidt, 1976). A strategy consists of a set of rules that may be defined as consistent relationships between two parameters of movement (Gottlieb, Corcos, & Agarwall, 1989a).

Fluctuating relationships among dependent and independent variables have confounded the issue of the relationships between variables of single-joint movements (Gottlieb, Corcos, & Agarwall, 1989a). Rules may exist among both dependent and independent variables. A dependent variable may include movement time, velocity, EMG amplitude, EMG burst duration, or errors. Rules between dependent variables demonstrate a relationship that is not directional and usually not causal. That is, peak agonist EMG activity and peak velocity (dependent variables) are both associated with distance (independent variable) moved. However, each dependent variable can independently increase or decrease with different distances. Independent variables are under control of the experimenter and may include manipulation of target size, movement distance, movement time or inertial load (Gottlieb, Corcos, & Agarwall, 1989a). Rules existing between dependent and independent variables have also been identified. This is observed in relationships between movements to various distances and with different inertial loads. For example, as target distance increases (independent variable) both movement time and velocity increase (dependent variables), while an increase in target size (independent variable) results in a decrease in movement time with a corresponding increase in velocity (dependent variable) (Fitts, 1954). Additionally, based upon the experimental design, a dependent variable may become an independent variable. For example, if movement time is constrained, then movement time becomes an independent variable.

There is no comprehensive model of general rules for governing single-joint movement. Some models explore descriptive relationships between kinetic and kinematic variables, EMG activity and trajectory control, or movement speed and accuracy, and are therefore limited to specific independent and dependent variables (Corcos, Gottlieb, & Agarwall, 1989, Fitts, 1954; Gordon & Ghez, 1987a; Gottlieb, Corcos, & Agarwall, 1989a, 1989b; Schmidt, 1988). Theoretically, a more comprehensive model of single-joint movement should predict multiple relationships among dependent and independent variables. A comprehensive model should provide a basis for the change in variable relationships in a variety of experimental paradigms. In addition, the model should predict the multiple variable relationships prior to the actual movement.

Some researchers have developed models which explain single-joint control by observing and then describing the movement based on a mathematical modeling of these observations (Newell & Corcos, 1993; Schmidt, 1979). Some of the basic models that describe relationships among dependent and independent variables include the impulse-timing model (Schmidt, 1979; Schmidt, Zelaznik, Hawkin, Frank, & Quinn, 1979), Fitts' (1954) speed-accuracy model, and Gordon and Ghez's (1987b) pulse-height model. The impulse-timing model proposes that a descending impulse controls movement. This model assumes that a motor program controls the amplitude and duration of the isometric force impulse, which in turn regulates force output. Force output is presumably controlled by either the initial burst of force or the time over which the force is transmitted. When either variable, the initial burst of force or force duration is controlled, the other variable is proportionally rescaled (Schmidt, 1988; Schmidt et al., 1979).

The speed-accuracy model describes the relationship between the speed of movement and target size. This model is based upon a logarithmic trade-off between movement speed and accuracy, with the trade-off relating to the accuracy component of the task. Therefore, this model accounts for adjustments in movement speed with corresponding changes in target size (Fitts, 1954; Newell & Corcos, 1993; Schmidt, 1988). This model appears to be limited to specific experimental paradigms and can only explain limited relationships among dependent and independent variables.

Speed-accuracy and impulse timing models have been associated with relationships between dependent and independent variables as a means of determining single-joint voluntary control. The pulse-height model expanded on these models with the addition of an instructional variable, as another independent variable, which could influence single-joint control (Gordon & Ghez, 1987b). Although instructions were provided in the previous models, the investigators did not classify and analyze instructions as an independent variable. Instructional variables are premovement instructions that are given to the participant by the experimenter; e.g., to execute the task within a certain time frame, as fast as possible, or as accurately as possible.

Developed for isometric contractions is the pulse-height model which suggests that force impulses are generated by rules governing pulse-height control (Gordon & Ghez, 1987b). That is, force impulses are proportionally scaled to allow responses of different amplitudes. The force impulse controls the rate of rise of force, while the control of force rise time depends upon the independent variable. In an accuracy task, force rise time is considered to be invariant. That is, force rise time presumably will not increase with increased peak force. However, in tasks in which there are no accuracy constraints, force rise time will increase with peak force. This model (pulse-height) is based upon the aimed force impulse which subsequently determines the trajectory of motion. The dual-strategy model expands upon the pulse-height model by providing further explanation as to the origin of control for single-joint movements.

Dual-Strategy Hypothesis

Gottlieb, Corcos, and Agarwall (1989b) developed the dual-strategy model based on the analysis of isotonic (concentric) movements as an alternate model for the control of single-joint voluntary movements. This model is dependent upon the concept of an excitation pulse, which activates the spinal motor neuron pool. There is no delineation as to the origin of the excitation pulse, but parameters that may influence the modulation of the excitation pulse are defined. The excitation pulse is used as an explanation for limb trajectories (peak force and rate of rise of force development) and EMG activity that could be affected by task changes (Gottlieb, Corcos, & Agarwall, 1989a, 1989b; Newell & Corcos, 1993). This model is similar to the pulse-height model with two exceptions. The pulse height model did not interrelate limb trajectory with EMG activity; nor does it provide an explanation for the origin of the isometric force impulse. Therefore, it appears the dual-strategy model better defines the programmed aspects of movement, while accounting for relationships among dependent and independent variables. Additionally, this model predicts the multiple variable relationships prior to the movement (Gottlieb, Corcos, & Agarwall, 1989a).

The dual-strategy hypothesis can account for isotonic movements across different distances, inertial loads, different target widths, and over different velocities (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Corcos, & Agarwall, 1989a, 1989b). The dual-strategy model is based upon three propositions: 1) movements are planned according to strategies which are a set of rules among independent variables, 2) the control of single-joint movements is based on at least two strategies which include SI and SS strategies, and 3) the choice between the strategies depend on the independent variable as to whether to control the speed of the movement (Gottlieb, Corcos, & Agarwall, 1989a).

Gottlieb, Corcos, and Agarwall (1989a) define the SI strategy as consisting of movements that are "insensitive" to the speed of the movement. Single-joint movements performed under this strategy lead to a linear relationships among peak accelerating torque and peak torque, peak velocity, and movement time. Additionally, when these variables are plotted against time, all initially rise along the same trajectory. These relationships still hold when independent variables, such as distance moved or inertial load, are changed. For example, as distance decreases, there is a linear decrease in peak velocity, peak torque, and movement time (Gottlieb, Corcos, & Agarwall, 1989a, 1989b).

The SS strategy consists of movements where speed is the independent variable, which may be implied either explicitly or implicitly. For example, participants are instructed to move within a given time period, to different sized targets at the same distance or to move as rapidly as possible. In the SS strategy, peak accelerating torques, and peak velocity increase linearly with a corresponding increase in movement speed. However, these measures initially rise along different trajectories Additionally, the SS and SI movement strategies each produce a characteristic pattern of muscular activity and torque profile.

EMG Activity and Torque

It has been implied those relationships between peak accelerating torque and EMG activity account for differences between the SS and SI strategies (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Corcos, & Agarwall, 1989b). The excitation pulse, in addition to controlling limb trajectory, should also modulate agonist EMG activity. To further analyze EMG activity, agonist activity was divided into two separate time periods. The first time period (Q_{30}) consisted of the first 30 ms of agonist activity. The agonist activity following the initial 30 ms until the end of force acceleration was described as Q acceleration (Q_{acc}) (Corcos, Gottlieb, & Agarwall, 1989). Depending upon the movement strategy, there were different relationships between EMG activity and peak accelerating torque in isotonic movements.

In the SI strategy, these two phases of EMG activity (Q_{30} and Q_{acc}) were represented by different relationships with peak accelerating torque. The variable, Q_{30}, was shown to be insensitive to the distance moved or inertial load. That is, Q_{30} did not appreciably change with the manipulation of movement distance or load (Gottlieb, Corcos, & Agarwall, 1989b). In contrast, there was a linear relationship between Q_{acc} and changes in the independent variables (Gottlieb, Corcos, & Agarwall, 1989b). Additionally, the SI strategy was ascertained to be the default strategy for movements where speed was not the independent variable (Gottlieb, Corcos, Agarwall, & Latash, 1990).

With the SS strategy, peak accelerating torque, Q_{30}, and Q_{acc} increased linearly with an increase in movement speed. For example, as the speed of the movement increased there was a corresponding increase between peak accelerating torque and Q_{acc}. This relationship was established for Q_{30} under the SS strategy (Corcos, Gottlieb, & Agarwall, 1989). Therefore, both Q_{30} and Q_{acc} were sensitive to the speed of movement. Additionally, the onset of antagonist EMG activity was delayed with increased movement times (Corcos, Gottlieb, & Agarwall, 1989).

Isometric Contractions

Corcos, Agarwall, Flaherty, and Gottlieb (1990) extended the dual-strategy model of single-joint control to describe isometric contractions. They proposed that isometric contractions are controlled in the same manner as single-joint isotonic movements, but were unable to fully support this assumption. However, Gordon and Ghez (1987) appear to have support for this assumption, because their evaluation of fast and accurate isometric contractions determined that the first measurable features of a response could predict the entire response. In this case, both the first and second time derivatives of force were used to predict the entire response. In the evaluation of isometric contractions by Corcos et al. (1990), movements performed under the SS strategy appear to support the dual-strategy hypothesis; however, ambiguity exists with the analysis of contractions performed under the SI strategy.

An analysis of the research on isometric movements by Corcos et al. (1990), appears to reveal some limitations in the design and subsequent analysis of the data. Gottlieb, Corcos, and Agarwall (1989b) previously stated that peak accelerating torque is the linking variable that could explain correlations between dependent and independent variables. Isotonic movements yield specific relationships between peak accelerating torque and EMG activity (Q_{30} and Q_{acc}) with the manipulation of independent variables, which can differentiate the two strategies (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Corcos, & Agarwall, 1989b). For example, with the SS strategy, peak accelerating torque and both Q_{30} and Q_{acc} increase linearly with an increase in movement speed. However, under the isometric condition, conclusions could not be drawn about the relationships of torque measures and EMG activity. Additionally, there appear to be some questions regarding the classification of the SI and SS tasks.

In a study by Corcos et al. (1989), elbow flexion and extension movements were performed to varying bandwidths with the same amount of force production. This was classified as an SI strategy. However, the participants were also asked to perform these movements at a comfortable speed. This added instruction made this task a combination of both strategies, which may have been a factor that influenced the lack of expected results for the different strategies. It appears that further research is required to determine if isometric contractions operate under a dual-strategy hypothesis.

Excitation Pulse

The dual-strategy model is based on EMG activity and torque trajectories being the consequences of the same initial control signal. The proposed control signal, the excitation pulse, should account for the different patterns of EMG activity and muscle torque trajectories that are dependent upon the movement strategy. Gottlieb, Corcos, and Agarwall (1989a) proposed that the excitation pulse could be controlled by altering either the pulse's height or width. This implied that two different mechanisms control the excitation pulse, which should correspond with the two different strategies of movement.

The excitation pulse is thought to have a uniform intensity when movements are carried out under the SI strategy. This intensity should not be influenced by task variables, such as moving different distances or loads. However, the width of the excitation pulse should vary in proportion to changes in the independent variables. This is described as pulse-width modulation (Gottlieb, Corcos, & Agarwall, 1989b). In contrast, the width of the excitation pulse should be held constant, while the amplitude of the excitation pulse should change in the SS strategy. Therefore, the intensity of the excitation pulse should be influenced by moving at different speeds. This is known as pulse-height modulation (Corcos, Gottlieb, & Agarwall, 1989).

According to the dual-strategy hypothesis, different movement strategies should produce different movement profiles as a consequence of changes in the excitation pulse. According to Gottlieb, Corcos, and Agarwall (1989a), the excitation pulse is reflected by the status of the excitability of the spinal motor neuron pool. The level of motor neuron excitability can be analyzed using the Hoffman reflex (H-reflex) (Hugon, 1973; Schieppati, 1987). Frank (1986) suggested that motor neuron pool excitability relates to the force and timing of the movement. Butler, Yue, and Darling (1993) indicated that the amplitude of the H-reflex linearly increases with force. This increase occurs up to 60% of a maximum voluntary contraction. After 60% of a maximum voluntary contraction, the H-reflex increases in curvilinear fashion. Since the excitation pulse may be predicted from inspection of EMG activity and limb trajectory, the relationships between EMG activity and limb trajectory may be compromised when force output exceeds 60% of a maximum voluntary contraction. In fact, some of the tasks in the Corcos et al. (1990) isometric study exceeded 60% of a maximum voluntary contraction. This may be a plausible explanation for the lack of conclusive results. Further research seems necessary to evaluate the potential relationships among the excitation pulse, EMG activity, and peak torque while isometric contractions are performed. Additionally, the existence of an excitation pulse and its potential relationship with spinal excitability warrants investigation. This will help to determine if different movement strategies are mediated at a spinal cord level.

Motor Neuron Reflex Excitability

Motor neuron pool excitability increases prior to the generation of plantar flexion torque (Brunt & Robichaud, 1996; Kagamihara, Komiyama, Ohi, & Tanaka, 1990; Mitchie, Clarke, Sinden, & Glue, 1976; Sullivan, 1980). This increase occurs 50 to 80 ms prior to EMG activity onset in a nonchoice ballistic task and is time-locked to the onset of the EMG activity (Brunt & Robichaud, 1996; Kots, 1977; Mitchie et al., 1976). This period of spinal cord facilitation implies the readiness of the central nervous system to implement the planned motor action (Brooks, 1986; Frank, 1986). If the excitation pulse is reflected in changes in spinal excitability, then changes in the period of spinal facilitation should correspond with changes in movement strategies that determine EMG and torque profiles.

There appears to be support for different movement strategies being reflected by changes in spinal cord excitability prior to onset of EMG activity. The dual-strategy hypothesis suggests that the SI strategy should be reflected in changes in the timing (pulse width) of spinal cord facilitation. Kagamihara et al. (1990) evaluated the time course of spinal facilitation in a ramp plantar flexion task. For the ramp task, the participant moved at a preselected cursor speed. The onset of spinal facilitation began at 92 ms prior to EMG onset. Additionally, Frank (1986) ascertained an increase in the time period of spinal cord facilitation (70 ms prior to EMG onset) with an anticipation timing task. The dual-strategy hypothesis proposes that the excitation pulse in an anticipation timing or ramp task should be classified as representing a SI strategy, since there is no requirement to control speed for either of these tasks. These examples appear to support pulse-width modulation of spinal cord facilitation, since the onset of spinal facilitation occurs later than 50 ms prior to EMG activity onset.

Because speed is the dominate feature of ballistic and step tasks, these movements would be classified as representing the use of an SS strategy according to the dual-strategy hypothesis and should show pulse-height modulation. Numerous studies have shown that the onset of spinal facilitation occurs between 55 and 80 ms prior to EMG onset in ballistic plantar flexion tasks (Brunt & Robichaud, 1996; Eichenberger & Ruegg, 1984; Manning & Hammond, 1990). Kagamihara et al. (1990) evaluated spinal facilitation in step and ramp plantar flexion tasks. In the step task, participants were requested to reach a target that was designated between 20 and 40% of the a maximum voluntary contraction. The step task showed an earlier onset of spinal facilitation (55 ms prior to EMG onset) when compared to the ramp task (92 ms prior to EMG onset). These results appear to support the pulse-height control for SS strategies.

Additionally, Eichenberger and Ruegg (1984) ascertained that shorter reaction times had greater amounts of spinal facilitation. This could be attributed to these tasks being carried out using an SS strategy, while longer reaction times may have defaulted to the SI strategy. Eichenberger and Ruegg (1984) implied that different movement strategies may have been used to perform the tasks. However, none of these studies were designed to analyze SS or SI strategies (e.g., pulse width or pulse height modulation) and modulation of spinal facilitation.

Single-joint isotonic movements can be classified according to the dual-strategy hypothesis. There is some ambiguity as to the ability of this hypothesis to be extended to isometric movements. The dual-strategy hypothesis asserts that single-joint movements can be classified into different strategies depending upon whether or not the speed of the movement is controlled. Different movement strategies may be determined by the type of neural excitation pulse. This excitation pulse presumably modulates spinal excitability that should reflect changes in the H-reflex.

The dual-strategy hypothesis appears to provide a model for unifying principles for the control of isotonic single-joint movement. Isometric movements have been evaluated to determine if these movements are governed by the same principles of single-joint movement. Research on isometric movements has not fully supported the existence of the dual-strategy model. However, an analysis point to limitations in the design of studies oriented toward determining this model's extension to isometric movements. This study is designed to examine isometric movements to see if the dual-strategy hypothesis can be extended to account for isometric movements. The potential neural mechanism (excitation pulse) that may govern the different strategies will also be evaluated.

Statement of Problem

The purpose of this study is to examine the relationship between EMG activity and torque trajectories during isometric contractions to determine if the dual-strategy model can be applied to these types of muscle contractions. Isometric contractions of the soleus muscle will be performed at two specified levels of force, which will be related to the maximum amount of force that a participant can produce. The force level will be maintained within a specified range of force. For example, participants may be asked to produce a force between 45% and 55% of their maximal force output. This would be defined as a 50% force level with a 10% range.

The dual-strategy hypothesis suggests that different strategies should produce different neural excitation pulses. This pulse, proposed to modulate spinal excitability, is thought to be reflected by changes in the H-reflex (Gottlieb, Corcos, & Agarwall, 1989a). The H-reflex is a noninvasive test that can be used to measure changes in spinal cord excitability. Evaluated will be the neural mechanism (excitation pulse) that may govern the different strategies.

Independent variables for this study will include 1) target variables of 5% and 15% bandwidths and 2) target variables requiring two specific isometric force contraction levels (25% and 50%) which will be based on a participant's maximum voluntary contraction. Additional dependent variables for evaluation of the neural excitation will include amplitude of the H-reflex, amplitude of the maximum M-response, and duration of H-reflex facilitation.

Research Hypotheses

The research hypotheses examined in two studies are as follows:

Study 1

The dual-strategy hypothesis was evaluated to determine whether this model can be extended to account for single-joint isometric movements. It was hypothesized that, isometric movements can be classified according to either an SS or SI strategy.

1. Hypotheses tested for the SS strategy are as follows:

   a. Single-joint isometric movements performed under the SS strategy will demonstrate that the slope of the first time derivative of force (dF/dt) will positively rise along different trajectories.

   b. Q_{30} and Q_{acc} of agonist EMG activity will positively rise with increases in bandwidths.

   c. The 5% bandwidth will result in a smaller amount of agonist EMG activity, slope of dF/dt, and peak dF/dt when compared with the 15% bandwidth for the respective force level.

With the SS strategy, peak accelerating torque, Q_{30}, and Q_{acc} have been shown to increase linearly with an increase in movement speed (Corcos, Gottlieb, & Agarwall, 1989b). For example, as the speed of the movement increases, there is a corresponding increase between peak accelerating torque and Q_{30} and Q_{acc}. Therefore, both Q_{30} and Q_{acc} are sensitive to the speed of movement.

2. Hypotheses tested under the SI strategy are as follows:

a. Single-joint isometric movements performed with the SI strategy will show that the slope of dF/dt will rise along the same trajectory.

b. Q_{30} will be invariant with either increases or decreases in maximum voluntary contractions.

c. The slope of force and Q_{acc} will result in a positive relationship with an increase in the maximum voluntary contraction.

d. A 50% maximum voluntary contraction will result in a larger amount of agonist EMG activity, and peak dF/dt when compared with the respective bandwidth at the 25% force level.

For the SI strategy, the two phases of EMG activity (Q_{30} and Q_{acc}) have been represented by different relationships with peak accelerating torque. The variable, Q_{30}, has been shown to be insensitive to the distance moved or inertial load. That is, Q_{30} does not appreciably change with the manipulation of movement distance or load (Gottlieb, Corcos, & Agarwall, 1989b). In contrast, a linear relationship has been obtained between Q_{acc} and changes in the independent variables (Gottlieb, Corcos, & Agarwall, 1989b).

Study 2

Different movement strategies were proposed to produce different neural excitation pulses. This neural pulse should be reflected by changes in motor neuron reflex excitability. The hypotheses tested were that single-joint isometric movements performed under the SS and SI strategies produce different intensities and patterns of motor neuron reflex excitability prior to EMG activity onset.

1. Hypotheses tested for the SS strategy are when force level is held constant and comparisons are made across bandwidths,
    a. The 5% bandwidth will produce the same duration of premovement H-reflex facilitation when compared to the 15% bandwidth.

b. The 5% bandwidth will produce a smaller slope of premovement facilitation when compared to the 15% bandwidth.

c. The 5% bandwidth will produce a smaller H-reflex peak to peak amplitude during premovement facilitation.

Because speed is the dominate feature of ballistic and step tasks, these movements would be classified as SS strategies according to the dual-strategy hypothesis and should exhibit pulse-height modulation. Numerous studies have shown that the onset of spinal facilitation occurs between 55 and 80 ms prior to EMG onset in ballistic plantar flexion tasks (Brunt & Robichaud, 1996; Eichenberger & Ruegg, 1983,1984; Manning & Hammond, 1990). Kagamihara et al. (1990) evaluated spinal facilitation in step and ramp plantar flexion tasks. The step task shows an earlier onset of spinal facilitation (55 ms prior to EMG onset) when compared to the ramp task (92 ms prior to EMG onset). These results appear to support the pulse-height control for SS strategies.

2. Hypotheses tested for the SI strategy are, when bandwidth is held constant and comparisons are made across force levels,

a. The 25% force level will produce a shorter duration of premovement facilitation when compared to the 50% force level.
b. The 25% force level will produce a smaller slope of premovement facilitation when compared to the 50% force level.
c. The 25% force level will produce a smaller H-reflex peak to peak amplitude during premovement facilitation.

The dual-strategy hypothesis suggests that the SI strategy should reflect changes in the timing (pulse width) of spinal cord facilitation. Kagamihara et al. (1990) evaluated the time course of spinal facilitation in a ramp plantar flexion task. In the ramp task, the participant moved at a preselected cursor speed. The onset of spinal facilitation began at 92 ms prior to EMG onset. Additionally, Frank (1986) observed that there was an increase in the time period of spinal cord facilitation (70 ms prior to EMG onset) with an anticipation timing task. The dual-strategy hypothesis proposes that the excitation pulse in an anticipation timing or ramp tasks should be classified as a SI strategy, since there is no requirement to control speed for either of these tasks. These examples appear to support pulse-width modulation of spinal cord facilitation, since the onset of spinal facilitation occurs later than 50 ms prior to EMG activity onset.

Operational Definitions

Terms defined for the purposes of this investigation are as follows:

Alpha motor neuron is a motor neuron that innervates extrafusal muscle fibers.

H/M ratio represents the percentage of motor neuron pool that is active at any particular time. This ratio is between the amplitude of the maximum M-response and the amplitude of the tested H-reflex.

H-reflex (Hoffman reflex) is an electrically stimulated monosynaptic reflex that excites the muscle spindle's Ia afferents. Action potentials are transmitted to the spinal cord where monosynaptic connections cause motor neurons to reach threshold, thereby causing the extrafusal muscle to fire.

Instructional variables are premovement instructions that are given to the participant by the experimenter. This may include instructions to perform the task within a certain time frame or as accurately as possible. These are considered independent variables.

Isometric contraction is a muscular contraction where there is no external movement of the contracting limb.

M-response is an electrically stimulated direct motor response. The maximum M-response that represents 100% of the activity of the specified muscle's motor neuron pool.

Measured variables are dependent variables that may include movement time, velocity, or EMG duration or amplitude.

Motor neuron reflex pool excitability is the net sum of all facilitatory and inhibitory influences from afferent and descending influences on the alpha and gamma motor neurons.

Premotor time is the time from the visual signal to onset of EMG activity.

Reaction time is the time from the visual signal until voluntary movement is initiated.

Strategy is a set of consistent rules for muscle activation that determine the pattern of EMG activity and torque trajectories.

Speed-insensitive strategy (SI) consists of movements that are insensitive to the speed of movement.

Speed-sensitive strategy (SS) consists of movements that are sensitive to the speed of movement.

Spinal cord facilitation is an increase in the excitability of the motor neuron pool that occurs prior to onset of EMG activity.

Basic Assumptions

The following assumptions were made:

1. Single-joint isometric movements can be classified according to different strategies. These strategies occur with changes in either specified force output or bandwidth. For example, when the task is to move to the same bandwidth at different levels of force output, the SI strategy is utilized.

2. Participants must remain on task. To help keep the participant on task, they were reminded to be as fast and accurate as possible after every 20 trials. Additionally, to help eliminate anticipation of the response, the muscle activity was monitored prior to the initiation signal. If muscle activity was present, participants were asked to relax their leg. Catch trials were also included to help the participant remain on task.

3. Differences between dependent variables in single-joint movements are due to participants using either the SS or SI strategy.

4. The SS and SI strategy are represented by differences in the excitation pulse (i.e., pulse width vs. pulse height).

5. The excitation pulse is represented by changes in alpha motor neuron excitability that can be assessed by changes in the H-reflex.

6. The H-reflex is a measure of alpha motor neuron excitability.

Limitations

Limitations for this study are perceived to be as follows:

1. The participant may not use the appropriate strategy while performing the different tasks. In order to reduce this possibility, participants were verbally reminded after every block of 20 trials to produce the task as fast and accurately as possible

2. The proposed neural excitation pulse may not be reflected by changes in the excitability of the motor neuron pool. This possibility was evaluated through pilot tests which indicated the existence of different neural pulses for the SS and SI strategy.

3. Isometric movements may not follow the dual-strategy paradigm. To help eliminate this possibility, pilot tests were run which indicated that isometric movements could be classified according to the dual-strategy paradigm.

4. Extraneous factors, such as any unnecessary movement, caffeine, learning, or ankle movement may influence the level of spinal excitability. These problems were controlled by having participants: a) seated in a custom

chair that limits head and ankle movement, b) refrain from caffeine intake 12 hours prior to the test, and c) go though a series of learning trials prior to the experiment. Participants performed 50 learning trials for each force level and bandwidth. After completing the trials, participants continued to perform trials until they were accurate on 9 out of 10 trials.

Significance of the Study

Movement dysfunction in patient populations, such as Parkinson disease or stroke, is not well understood. Until research can identify the precise nature of dysfunction that produces cognitive, programming, or execution deficits, the most appropriate method for motor relearning or rehabilitation will be difficult to determine.

No comprehensive model analyzing programming and execution components of movement dysfunction has been established. A recent model of single-joint control, the dual-strategy hypothesis, was developed by Gottlieb, Corcos, and Agarwall (1989). This model divides movements into speed sensitive (SS) and speed insensitive (SI) strategies, with the same initial impulse modulating both force trajectories and EMG activity. Specific relationships between these parameters differentiate the movement strategies. The "neural pulse" is indicated to be the initial impulse, which is assumed to reflect motor neuron pool excitability. Different movement strategies should produce different neural pulse patterns. For example, the SS strategy should modulate neural pulse height, while the SI strategy may alter the neural pulse width.

Although Gottlieb and colleagues (1989) outlined specific relationships between torque trajectories and agonist activity with movement strategy, there was no attempt to examine the existence of the neural pulse or to show relationships between this pulse and motor programming. Evidence suggests different neural pulses are represented by changes in motor neuron excitability. For example, in an anticipation timing task that could be classified as an SI strategy, Frank (1986) ascertained an increase in the time period of motor neuron excitability prior to onset of EMG activity. This would be classified as pulse-width modulation. The neural pulse of different movements was evaluated by measuring changes in spinal excitability prior to movement onset. The dual-strategy hypothesis allows detailed evaluation of single-joint isotonic movement. Ambiguity existed as to whether isometric contractions can be classified by this model. The generalizability of this model was analyzed by evaluating programming and neural changes of single-joint isometric movements.

The evaluation of the parameters of spinal cord excitability may aid in understanding the preparation of motor neuron excitability prior to the movement. Additionally, a comprehensive model of single-joint control would enhance the ability of the practitioner to equate differences in force trajectories and parameters of muscle activity with specific neurological deficits. This information would assist in determining which neurological conditions produce cognitive, programming, or execution deficits in the performance of the desired movement. This may add information into the differences between force and timing components of movements, which would help in the analysis of movement dysfunction. For example, such information may help determine if Parkinson disease produces timing or force production (as suggested from the results of Horak, 1984) movement deficits. Physical therapists would benefit from this knowledge in designing patient treatment plans by being able to focus treatments on actual movement deficits. For example, therapists would be able to focus therapeutic interventions that help the patient either access or execute the motor program for the desired movement.

CHAPTER 2
REVIEW OF LITERATURE

Woodworth (1899) proposed that single-joint movements were controlled by two phases of movement. Later, according to Latash, Bernstein described voluntary movements as being controlled by higher centers within the central nervous system (Latash, 1989). Higher centers were described as a "black box", with input/output relationships between internal structures controlling voluntary movement. In this analogy, there were many levels of control with each level having functional importance in the control of voluntary movements (Latash, 1989). Bernstein (1967) further evaluated the ability of the motor system to overcome the apparent redundancy of joint angles or "degrees of freedom" when performing a voluntary task. In particular, he noted that when blacksmiths used a hammer to hit a chisel, there was a small variability at the endpoint of movement, eventhough, there was a high variability of joint angles. From this observation, Bernstein deduced that the central nervous system controls movements by reducing or eliminating redundant degrees of freedom. At the time of Woodworth's and Bernstein's original hypotheses, the underlying mechanisms and structures within the central nervous system were not well understood.

No current model of multi- or single-joint control has been developed to fully analyze programming and executive components of single-joint movements. Research oriented toward the evaluation of single-joint movements may be advantageous because of the inherent difficulties with attempting to control multi-joint movements. However, a recent model of single-joint movements by Gottlieb, Corcos, and Agarwall (1989a) has described characteristic relationships between EMG activity and torque trajectories during isotonic movements. This model, the dual-strategy hypothesis, divided movements into SS and SI strategies, with the different strategies utilizing a different set of rules for single-joint isotonic tasks (Gottlieb, Chen, & Corcos, 1995; Gottlieb, Corcos, & Agarwall, 1989a). However, ambiguity existed as to the precise nature of these relationships in isometric tasks (Corcos, Agarwall, Flaherty, & Gottlieb, 1990; Gottlieb, Corcos, & Agarwall, 1989a).

The utilization of the SS or SI strategy was proposed to correspond with a different modulation of excitation pulse converging onto the motor neuron pool (Gordon & Ghez, 1987b; Gottlieb, Corcos, & Agarwall, 1989a; Jaric, Corcos, Agarwall, & Gottlieb, 1993). The excitation pulse should be reflected by different patterns of motor neuron pool excitability prior to the movement. For example, different strategies may modulate either the amplitude or duration of the excitation pulse. The existence of the hypothesized excitation pulse has not been investigated. However, the neuromuscular system does produce characteristic changes in motor neuron pool excitability prior to a voluntary movement (Brunt & Robichaud, 1996; Eichenberger & Ruegg, 1984; Riedo & Ruegg, 1988). These changes have been investigated in conjunction with premotor reaction, response, motor, and movement times. Simultaneous investigation of motor neuron pool excitability during both an SS and SI voluntary isometric movement may allow the analysis of the hypothesized excitation pulse. That is, a comparison of spinal excitability patterns could be evaluated between the SI and SS strategies.

This review will examine the relationships between torque trajectories and agonist EMG activity of single-joint isometric movements to evaluate whether the dual-strategy hypothesis can be extended to account for isometric movements. The review of single-joint movements will cover both motor programs and models of programmed movements. The discussion will be limited to models of motor control that are testable in terms of central nervous system functioning. This is not to discount other models, such as the dynamical theory or Kelso's co-ordinateive structure model. However such models do not specify the control of movement in terms of a structured code within the central nervous system and therefore are not currently testable using a neurophysiological approach to movement. The specific models that will be discussed include: Fitts' speed/accuracy tradeoff model, the impulse timing model, the pulse height model, and the dual-strategy model. Reference to the dual-strategy model will include discussion of the SS and SI strategies during both isotonic and isometric contractions. The relationship between single-joint movements and EMG activity will be analyzed. Additionally, the proposed excitation pulse which may modulate the dual-strategy hypothesis will be reviewed. This analysis will include the relationship of motor neuron excitability with 1) voluntary movement, 2) force output, 3) reaction time, and 4) the SS and SI strategies.

Motor Programs

Lashely (1951) was one of the first motor theorist to propose that movements were centrally controlled. The central control of voluntary movements has subsequently been described as the "memory drum theory" by Henry and Rodgers (1960) and more recently as a "motor program" by Keele (1969) and Schmidt (1976). In the memory drum theory, Henry and Rodgers (1960) ascertained that reaction time increased with the number of required movements. It was proposed that movement information was loaded into a buffer, termed a “memory drum”, after the initiation signal. The larger the number of required movements subsequently increased buffer loading time and reaction time. This interpretation has been supported by the work of Sternberg and colleagues (1978).

Schmidt (1976) expanded on the motor drum theory by introducing the concept of a motor program that controlled voluntary movements. A motor program was defined as a centrally stored prestructured set of muscle commands which carry out movement without feedback about the goal of the movement. However, there were two areas of concern with the concept of a motor program (Schmidt, 1975). The first difficulty encompassed a storage problem, where the assumption was a one-to-one relationship between a motor program and each motor response. This assumption required a large number of motor programs and central storage area to account for all possible movements. The capability to store numerous motor programs have not been disproved, but the question of storage remained an issue. The second concern involved the "novelty problem", described as the ability to produce novel movements under new circumstances and environmental conditions which require new, adapted, or modified movement for success. The problem was whether a new movement was adapted from a previously stored motor program or required the generation of an entirely new motor program.

The "generalized motor program" or “schema theory” was therefore formulated to address the concerns with storage and novel movements (Schmidt 1975). The schema theory, like the original motor program, acknowledged a centrally stored, prestructured set of muscle commands for carrying out a class or category of movements. However, the assumption of a one-to-one relationship between the motor program and a motor response produced was replaced by a one-to-many view (Schmidt, 1975). Variations of motor responses within a movement class arose from altering parameters of the motor program (or schema), such as movement speed or force. This perspective provided an explanation for the generation of novel movements by changing the response specifications of the schema for a class of movements.

A schema was further theorized by Schmidt (1975, 1976) to be composed of invariant and variant features. Invariant features were aspects which were fundamentally structured in the schema and common to the generalized motor program. The order of events, temporal structure of muscle contractions, and the relative force have all been implicated as invariant features of the schema. Variant features are those dimensions or parameters of the schema that were relatively superficial and temporary. Selecting variant features or parameters such as force and duration afforded a variety of movement responses within a generalized motor program (Brooks, 1986; Schmidt, 1988).

Investigations about the production of a motor program have addressed issues such as the required programming time related to movement complexity (Fischman, 1984), programming force, timing components, (Ivry, 1986), and the effects of force variation on the motor program (Ito, 1990). The effects of the above parameters on motor programming, have been evaluated during simple and choice reaction time studies by fractionating reaction time into premotor and motor time. Premotor time has been defined as the time between the onset of a stimulus for movement and the onset of EMG activity. Premotor time represents the time required to centrally organize, select and transfer the appropriate commands to the muscles for initiation and execution of the movement. Motor time can be described as the interval of time between the onset of EMG activity in the selected muscle above the baseline activity and the initiation of the response. This may be representative of the peripheral processes of the response. Therefore, reaction time should equal to the sum of premotor time and motor time (Schmidt, 1988).

Fischman (1984) has stated that premotor time served as a more valid representation of programming time rather than reaction time alone. He asserted, that without fractionation of simple reaction time, it would be difficult to discern whether changes in total reaction time were due to central processes, peripheral processes, or another variable. Central processing time was identified as the time required to access the underlying motor program. Based upon this assumption, both Fischman (1984) and Ito (1990) used fractionated reaction time in their methodology to distinguish difference between the central and peripheral processes presumably associated with motor programming. The regularities of single and multi-joint movements have led investigators to propose various models for performing voluntary movements.

Models of Programmed Movements

Single-joint movements have been described by consistent relationships between observable features such a EMG activity (agonist duration and magnitude) and kinematic trajectories (force-time curves). For example, the duration of agonist EMG burst activity can be associated with the acceleration of the movement. That is, a positive linear relationship existed between the duration of agonist EMG activity and movement acceleration. This, plus other, observations have led to the view that a general relationship exists between agonist EMG activity and kinematic measures (Cooke, & Brown, 1994). However, the above assumption was contrasted by Hoffman and Stick (1993) and Gottlieb et al. (1989). These researchers proposed that agonist burst EMG activity and kinematic parameters can be independently specified by the nervous system. Gottlieb et al. (1989) went further to describe all single-joint movements as being based upon two separate movement strategies. A strategy "consists of sets of rules for muscle activation {that lead to} patterns of muscle torques and EMG activity ...[which] are highly and consistently correlated irrespective of task" (Gottlieb, Chen, & Corcos, 1995). Therefore, single-joint movements may be classified by different strategies which are based upon rules for EMG and kinematic measures.

Rules for single-joint movements consist of consistent relationships between two parameters of movement. Rules may exist among both dependent and independent measures. Dependent measures may include movement time, velocity, EMG amplitude, EMG burst duration, or errors. An example of rules among dependent variables includes the relationship between peak agonist EMG activity and peak velocity, which can both be associated with distance (independent variable) moved. However, there may be an independent increase or decrease among the dependent variables which can change with the independent variable. Independent variables are under control of the experimenter and include the manipulation of target size, movement distance, movement time or inertial load (Gottlieb, Corcos, & Agarwall, 1989a). Independent variables were considered to be directional and may affect the dependent variables, however, dependent variables could not affect the independent variable. Rules existing between independent and dependent variables have also been identified (Gottlieb, Corcos, & Agarwall, 1989a). This can be seen in relationships between movements to various distances, bandwidths, and with different inertial loads. For example, as target distance increased (independent variable) both movement time and velocity increased (dependent variables). Additionally, an increased target size (independent variable) resulted in a decrease in movement time with a corresponding increase in velocity (dependent variable) (Fitts, 1954; Gottlieb, Chen, & Corcos, 1995; Gottlieb, Corcos, & Agarwall, 1989a).

Based upon the experimental design, a previous dependent variable may become a independent variable. For example, if movement time was constrained it will become an independent variable. These fluctuating relationships among dependent and independent variables have confounded the issue of the relationships between these variables of single-joint movements. This tends to limit the generalizability of most models in explaining many aspects of single-joint movements. Eventhough controversy exists regarding an appropriate model for a model for single-joint movements, evidence suggests that these movements will be programmed in advance (Alexander, & Crutcher 1990a, 1990b; Crutcher & Alexander 1990).

Voluntary ballistic movements are planned and programmed in advance (Brooks, 1986). An analysis of Woodworth's (1899) original concept of control of limb trajectory provides insight into programmed movements. Woodworth (1899) theorized movements are controlled by two phases of movement. The first phase determined the limb's initial trajectory while the second phase directed the limb to the final target. The initial phase may be considered the motor program for implementing the movement, therefore there should be some predictable patterns that are consistent from task to task. These predictable patterned responses have eluded motor control theorists. The second phase was postulated to be influenced by visual or kinesthetic input which brought about movement corrections which may not be preprogrammed (Rosenbaum, 1991; Schmidt, 1988).

The notion that ballistic movements are totally preprogrammed arises from the concept that rapid movements are to fast to contain corrective adjustments (Desmendt & Godaux, 1978). However, this point has been disputed because corrective adjustments can be made in a time period too brief to be based purely on feedback from the movement (Gordon & Ghez, 1989a; Vicario & Ghez, 1984). The implication is that movements may be adjusted by a feed forward mechanism. Even though certain aspects of the movement may be modified, the earliest portion of the movement may still be preprogrammed.

No comprehensive model exists in which programming and execution components of single-joint movements have been analyzed. Woodworth's (1899) original hypothesis has not has not been discounted and many subsequent investigators have suggested various models for governing single-joint movement. These include the models proposed by Schmidt and colleagues' (1979) impulse-timing model, Fitts' (1954) speed-accuracy model, Gordon and Ghez's (1989a) pulse-height model, and Gottlieb and colleagues' (1989a) dual-strategy model. These models all incorporate different descriptions between kinetic and kinematic variables, relationships between EMG and trajectory control, or relationships between movement speed and accuracy. However, most models appear to explain only certain aspects of the movement and can usually only be associated with specific experimental paradigms.

Fitts' Model

In 1954, Fitts evaluated the relationship between speed and accuracy of simple aiming movements. Fitts assessed a reciprocal tapping task that was not thought to require central processing, therefore fundamentally different from the simple aiming movements used by Woodworth (1899). In Fitts' paradigm, subjects were instructed to tap as fast and accurately as possible between two targets with the manipulation of target width and inter-target distance (amplitude). Relationships between movement time, movement amplitude, and target width were established as a result of this paradigm. The relationship was related to the difficulty of the task.

Task difficulty, known as the index of difficulty (Id), was ascertained to be the mathematical relationship of two times the logarithm (to the base 2) of the movement amplitude divided by the target width. That is, $Id = \log_2 2A/W$, where A equals the amplitude of the movement and W equals the width of the target. This indicated that movement time increased when tapping movements were directed toward smaller targets or targets were moved further away (Fitts, 1954). The movement time to distance relationship was presumed to be produced by corrective submovements which were executed after visual feedback. This has become known as the speed/accuracy trade-off which relates to the accuracy component of the task (Newell & Corcos, 1993; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). That is, depending upon whether a person performs the task "as fast" or "as accurately" as possible, the other variable will presumably be sacrificed.

Schmidt (1979) and Meyer et al. (1982) analyzed isometric movement under the assumption that movements were not comprised of a set of discrete submovements. Under this assumption, a linear relationship between speed and accuracy resulted which were different from the logarithmic relationship produced when distance was controlled. This was contrary to Fitts' law and Meyer (1990) suggested movements that do not utilize feedback-based corrections will not exhibit the logarithmic relationship between speed and accuracy (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, & Wright, 1982). There have been several research reports which support the linear speed/accuracy trade off in isometric movements (Wright & Meyer, 1983; Zelaznik, Mone, McCabe, & Thaman, 1988; Zelaznik, Shapiro, & McColsky, 1981). Additionally, Klapp (1975) showed that with easy movements (reaction times less than 200 ms) there was no relationship between the index of difficulty and movement duration. Keele (1968) also established a linear relation between movement speed and spatial variability.

Crossman and Goodeve (1983) proposed a theory to account for Fitts’ law. In this theory, based upon feedback control of movement, it was assumed that a series of corrections can impact response accuracy. Movements made over longer distances or to smaller targets presumably required more corrections and therefore more time. Keele (1986) also showed this feedback-based assumption for the control of movements which appeared to support Fitts’ law. Keele (1986) indicated that movement time was related to the number of corrections required to achieve the target. This notion accounted well for Fitts' law and supported the feedback-based idea of motor control. However, the use of feedback may pose a problem with Fitts’ law.

Evidence appears to indicate that subjects have difficulty processing feedback during movements that take less than 200 ms. (Schmidt, 1976). Therefore, fast reaction times may not be conducive to on-line response corrections. From this perspective, the feedback-based idea for Fitts’ law can not account for all the experimental data. Crossman and Goodeve (1983) evaluated the limitations of error correction and concluded that short movement sequences may be run off without any peripheral feedback. This notion appeared to support the assumption that movements may be performed by prestructured muscle commands, which have been termed a motor program or schema (Keele, 1969; Schmidt, 1975, 1976).

The Fitts' paradigm involved a closed loop process which required sufficient time for feedback. This was contrary to Woodworth's (1899) assumption that rapid movements do not require visual control. Behavioral evidence appeared to support Fitts' law for single arm movements performed in both air or water (Fitts & Peterson 1964; Kerr, 1973). More recent models of motor control have extended past the observational data, which Fitts' model was based upon. These models, which include the impulse timing model, pulse height model, and the dual-strategy model, all have added a central nervous system component when explaining the control of voluntary movements.

Impulse Timing Model

The impulse timing model was developed using a centrally mediated impulse which controlled the movement. The impulse of electrical activity delivered to muscles may be characterized by acceleration and force-time functions with a motor program controlling the onset, amplitude, and duration of the impulse (Schmidt, 1976). The total impulse should be proportional to the area under the acceleration-time curve, with impulse duration being proportional to movement time, while impulse height should be inversely proportional to movement time (Jeannord, 1991; Schmidt, 1976).

The impulse timing model include the following force/time assumptions: 1) movements that are velocity-constrained produce a sinusoidal like force-time function, 2) force-time functions are controlled as a unit, such that with alteration of muscular force the force-time function will be proportionally rescaled, and 3) force-time functions can be captured by the impulse's amplitude and duration (Jeannord, 1991; Schmidt, 1988; Schmidt et al., 1979). The impulses' amplitude and duration may be controlled by altering either the force burst or the time over the transmitted force (Schmidt, 1988). Therefore, force-time and the duration of force can vary independently and be appropriately rescaled to the other parameter without affecting the goal. For example, force may be increased while holding the timing of the movement constant. This would produce movements with the same duration, however the amplitude of the movement would became progressively larger with increased force.

The applied impulse may relate to the magnitude of force output and may dictate the pattern of movement and muscle contraction relative to the desired force. There appears to be a proportional relationship between the applied impulse and force and force variability, with the variability of the impulse being related to the impulse duration. One problem with this model was the implication that these impulses were only sent to agonist muscles. Therefore, no account for deceleration forces was provided (Bizzi, 1982, 1984; Meyer, 1982).

The assumption that the force-time function can be rescaled has been evaluated. Meyer (1982) showed that time and force were rescalable functions with the intensity and duration of the impulse being similarly scaled to the amplitude and period of a sine function. An implication of the rescalable properties of force and time implied that both these parameters can vary independently. For example, Freund and Budinger (1978) showed that force would be rescaled when movement time remained constant in an aimed target movement. Additionally, movement time and distance have been shown to change by altering the entire acceleration/time profile as a unit (Schmidt, 1988).

Behavioral evidence does not support the force-time rescalable function. Zelazink et al. (1986) analyzed kinematic data of aimed hand movements and showed a strong linear relation between target width and distance/time. However, time to peak acceleration was not related to time, but was fixed across different values of time. The impulse-timing model utilizes kinematic as a evidence for a central mediated impulse which controls movement. However, this model does not include any explanation as to the origin of the hypothesized impulse, nor does it incorporate any measures or muscle activity into the model.

Pulse-Height Model

Gordon and Ghez's (1987a) pulse-height model expanded on the previous models by adding EMG activity and an instructional variable as a parameter which can influence single-joint movement. Instructional variables were premovement instructions that were given to the subject by the experimenter. For example, the subject may have been told to execute the task within a certain time frame, as fast as possible, or as accurately as possible.

Gordon and Ghez (1987a) evaluated isometric forces to establish the presence of a control policy that modulated force production. Subjects performed elbow flexion isometric movements under the instructional sets of "fast" or "accurate". They were requested to make no corrective adjustments during the movement. Through a series of experiments, invariant relationships between limb trajectories and EMG activity allowed the inference of control policies which appeared to be operated by a motor program.

The tasks were designed to have subjects perform fast and accurate movements under three different force (37% to 53% of a subject's maximum voluntary contraction at the ratio of 1:2 and 1:3) levels at a 16% bandwidth. Each condition revealed similar linking variables of the initial peaks of the 1st (Force velocity - dF/dt) and 2nd (Force acceleration

- d^2F/dt^2) time derivative of force being strongly predictive of peak force. However, there were several differences noted between these conditions. The accurate condition was less variable and was related to longer force rise times. There was no dependence between force rise time and peak force, with force rise time remaining around a constant value. There was clear triphasic EMG activity with increased agonist activity in the fast condition. Agonist muscle activity increased with force, while the antagonist muscle activity and duration remained unchanged. However, the antagonist muscle activity varied with force rise time (Ghez & Gordon, 1987; Gordon & Ghez, 1987a).

The pulse-height model suggested that torque pulses were generated by rules governing pulse-height control, with the first measurable feature of the response predicted the entire response. That is, torque pulses were proportionally scaled to allow responses of different amplitudes. The scaling of this impulse can be influenced by the instructions provided to the participant. The instruction to move accurately affected the rate of rise of force, while force rise time was held constant. In the fast condition, force rise time was not regulated (Gordon & Ghez, 1987a). However, there was no attempt to utilize this model to explain results of past studies or to provide an origin for the actual control of the torque pulse.

Dual-Strategy Model

Gottlieb, Corcos, and Agarwall (1989a) developed the dual-strategy model as a universal model which described the control of single-joint voluntary movements. This model defined the programmed aspects of movement and accounted for relationships among dependent and independent variables. Single-joint voluntary movements across different distances, with different inertial loads, toward targets of different widths and over a wide range of experimentally manipulated velocities can be explained using the dual-strategy model (Latash & Gottlieb, 1992). This model was based on three propositions: 1) movements were planned according to "strategies" which were based on a set of rules associated with the nature of the task and the instructions provided to the performer, 2) the control of single-joint voluntary movements was based on at least two strategies, which include the SI and SS strategies, and 3) the choice between the SI and SS strategies depends on whether or not movement speed was controlled during the task (Gottlieb, Chen, & Corcos, 1995; Gottlieb, Corcos, & Agarwall, 1989a).

The dual-strategy model was based on regulation of the net presynaptic input on the alpha motor neurons of the agonist and antagonist muscles. The control signal was modeled as a rectangular excitation pulse, whose origin was not delineated; however, parameters which may influence the modulation of the excitation pulse were defined (Corcos, Jaric, Agarwall, & Gottlieb, 1993; Gottlieb, Corcos, Agarwall, & Lattash, 1990). The excitation pulse's amplitude and duration was presumably controlled by the central nervous system. The excitation pulse was thought to be controlled by altering either the excitation pulse's height or width. That is, an increase in the height of the pulse would indicate pulse-height control, while an increase in the length of the pulse would correspond to pulse-width control. Therefore, two different mechanisms for controlling the excitation pulse which correspond with the two different strategies of movement were indicated. According to Gottlieb, Corcos, and Agarwall (1989a), this excitation pulse should be reflected by the changes in the status of the excitability of the spinal motor neuron pool (Gottlieb et al., 1990).

The dual-strategy model assumed that agonist EMG activity and limb trajectories were consequences of the same initial excitation pulse. Relationships were ascertained between peak accelerating torque and EMG activity which were dependent upon whether or not movement speed was controlled during the task. To further analyze EMG activity, agonist activity was divided into two separate time periods. The first time period (Q_{30}) consists of the first 30 ms of agonist activity. The agonist activity after the initial 30 ms until the end of acceleration was described as Q acceleration (Q_{acc}). Depending upon the movement strategy (SS or SI), different relationships were observed between peak accelerating torque and the two phases of EMG activity during isotonic movements (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Corcos, & Agarwall, 1989b). In addition to differences in EMG activity, there were other measures which differentiated the SS and SI strategies.

Speed-insensitive strategy

The SI strategy was ascertained to be the standard and default strategy for single-joint voluntary movements. This strategy was considered to be insensitive to movement speed. For example, SI strategies were utilized when movements were performed to the same bandwidth but to different distances, or when the task was to move the same distance but different loads were applied to the limb. A linear relationship was obtained between peak accelerating torque and the measured variables of peak torque, peak velocity, and movement time when single-joint voluntary movements were performed under this strategy. These variables initially rose along the same trajectory and these relationships held when task variables such as distance moved or inertial load were changed. For example, as distance decreased, there was a linear decrease in peak velocity, peak torque, and movement time (Gottlieb, Corcos, & Agarwall, 1989a, 1989b).

The burst activity of the agonist muscle was shown to initially rise at a uniform rate. The duration of the rising phase and peak amplitude of the EMG activity varied in proportion to changes in distance or load. The initial acceleration segments over the first 30 to 50 ms were insensitive to the distance moved. There were different relationships with peak accelerating torque and the two phases of agonist EMG activity. The variable, Q_{30}, was shown to be insensitive to the distance moved or inertial load (task variables). That is, Q_{30} did not appreciably change with the manipulation of movement distance or load (Gottlieb, Corcos, & Agarwall, 1989b; Jaric, Corcos, Agarwall, & Gottlieb, 1993). In contrast, there was a linear relationship for Q_{acc} with changes in the task variable (Gottlieb, Corcos, & Agarwall, 1989b). The antagonist bursts vary similarly and had latencies that increased with the magnitude of the task variable. Additionally, the SI strategy was implicated as the default strategy for movements where speed was not explicitly or implicitly implied as the independent variable (Gottlieb et al., 1990).

Speed-sensitive strategy

The SS strategy consisted of movements where speed was either explicitly or implicitly implied as a independent variable. For example, subjects were instructed to move in a given time period, to different sized targets at the same distance or to move as rapidly as possible. Peak accelerating torques and peak velocity were shown to linearly increase with an increase in movement speed when movements were performed under this strategy (Jaric, Corcos, Agarwall, & Gottlieb, 1993). However, these variables initially rose along different trajectories. Peak accelerating torque and both Q_{30} and Q_{acc} both increased linearly with increased movement speed. For example, as movement speed increased there was a corresponding increase between peak accelerating torque and Q_{acc}. This relationship was also established for Q_{30} (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Chen, & Corcos, 1995). Therefore, both Q_{30} and Q_{acc} were sensitive to movement speed. Antagonist bursts varied similarly and had latencies that increased with movement time. Additionally, the onset of antagonist EMG activity was delayed with an increase in movement time (Corcos, Gottlieb, & Agarwall, 1989). The ability to differentiate the SS and SI strategies was based upon specific pattern differences in agonist and antagonist EMG activity (Corcos, Jaric, Agarwal, & Gottlieb, 1993; Jaric, Corcos, Agarwal, & Gottlieb, 1993). These differences should be reflected by different build up patterns of motor neuron excitability prior to the movement.

Excitation Pulse

The dual-strategy model, based upon an excitation pulse, should account for the different patterns of EMG activity and muscle torque trajectories which appeared to be dependent upon the movement strategy (Gottlieb, Corcos, & Agarwall, 1989a). This excitation pulse may be modified depending upon which movement strategy was utilized by a person (Gottlieb, Corcos, & Agarwall, 1989b; Newell & Corcos, 1993).

Single-joint movements performed under the SI strategy produce different movement profiles as a consequence of changing the width of the excitation pulse. The width of the excitation pulse should vary proportionally with changes in task variables, such as distance moved or inertial load. However, the intensity of the excitation pulse should be held constant. This has been described as pulse-width modulation (Gottlieb, Corcos, & Agarwall, 1989b).

Single-joint movements performed under the SS strategy produce different movement profiles as a consequence of a change in the height of the excitation pulse, while the width of the excitation pulse should remain uniform. The uniform intensity of the excitation pulse should not be a product of movement speed, with submaximal speeds being associated with submaximal intensities. The submaximal intensities may be selected features of the pattern of movement control. The intensity of the excitation pulse should vary with changes in movement speed. For example, movements performed to the same distance at different bandwidths should show modulation of the intensity of the excitation pulse, while the duration of the excitation pulse should be held constant (Gottlieb, Corcos, & Agarwall, 1989b). This has been described as pulse-height modulation (Gottlieb, Corcos, & Agarwall, 1989b). The dual-strategy model was initially utilized to explain single-joint isotonic movements, however evidence suggests this model may be applied to isometric movements.

Isometric Contractions

Corcos, Agarwall, Flaherty, and Gottlieb (1990) extended the dual-strategy model of single-joint control to include isometric contractions. They proposed that isometric contractions were controlled in the same manner as single-joint isotonic movements, but this assumption has never fully been supported. Gordon and Ghez (1987a) appear to support this assumption because their evaluation of fast and accurate isometric contractions established that the first measurable features of a response (e.g. the first and second time derivatives of force) could be used to predict the entire response. In the evaluation of isometric contractions by Corcos et al. (1990), movements performed under the SS or SI strategies appeared to be a blending of the two strategies patterns.

An analysis on the research on isometric contractions by Corcos et al. (1990), seemed to indicate some limitations in their research design and subsequent analysis of their data. Gottlieb, Corcos, and Agarwall (1989b) previously stated that peak accelerating torque was the linking variable that could explain correlations between dependent and independent variables. The research analyzing isotonic movements demonstrated specific relationships between peak accelerating torque and EMG activity (Q_{30} and Q_{acc}) with the manipulation of independent variables, which could differentiate the SS and SI strategies (Corcos, Gottlieb, & Agarwall, 1989; Gottlieb, Corcos, & Agarwall, 1989b). However, under the isometric condition there was insufficient analysis between torque variables and the dependent variables to draw sufficient conclusions.

Additionally, there appeared to be some conflict in the classification of the SI and SS tasks. For example, subjects performed four different levels of a maximum voluntary contraction to the same bandwidth under two different instructional sets. The instructions were to perform the task as fast and accurately as possible and then at a comfortable speed. The performance of a task to the same bandwidth at four different levels of a maximum voluntary contraction would be classified as an SI strategy. However, when the instructions to move at a comfortable speed were added, the task became a combination of SS and SI strategies. There appeared to have been some interplay between the SS and SI strategies in this isometric study.

Researchers concerned with isotonic single-joint movements have analyzed torque trajectories and EMG activity changes between the same amount of force and bandwidth changes of 3%, 6%, 9% and 12% of a specified maximum voluntary contraction. This task should be classified as an SS strategy. However, this paradigm appeared to indicate a division between the SS and SI (Corcos, Agarwal, Flaherty, & Gottlieb, 1990). Bandwidths were manipulated between 1.5° to 12° for a 54° target in a study by Corcos et al. (1990). A visual analysis of the data appeared to indicate that relationships between peak accelerating torque and EMG activity were dependent upon the specific bandwidth. That is, the relationship between peak accelerating torque and Q_{30} seemed to be invariant with the bandwidths of 1.5° and 3° for a 54° target, while there was an apparent linear relationship between these variables and the larger bandwidth targets (6° and 12° of a 54° target). For example, when subjects performed under the larger bandwidths they appeared to be performing under an SI strategy strategies (Corcos, Gottlieb, & Agarwal, 1989). That is, the bandwidth became large enough to no longer influence the movement. This appeared to suggest that for smaller targets individuals performed under the SS strategy, while performance under the SI strategy occurred to the larger targets. It appeared there may be a critical bandwidth whereby subjects performed under either the SI or SS strategy. Further research is required to differentially determine if isometric contractions operate under a dual-strategy hypothesis. Additionally, there appears to be characteristic muscle activity patterns which differentiate the SS and SI strategies.

Electromyographic Activity

Ballistic movements have been described by characteristic patterns of EMG activity where an agonist burst was followed by a silent period prior to a second agonist burst (Halite & Khoshibin, 1980). EMG activity demonstrated a temporal pattern between the agonist and antagonist muscles. There was a discharge from neural cells in the motor cortex prior to and during voluntary movement (Evarts & Fromn, 1978; Freud & Budinger, 1978; Garland, 1972). These observations appear to provide evidence that the early stages of ballistic movements can be centrally programmed and under the control of higher centers (Hallett & Khoshibin, 1980; Nagasaki, Irie, & Nakamura, 1983).

Several relationships have been established between force generation and EMG activity. (Yonenda, Oishi, & Ishida, 1983) The timing and duration of agonist and antagonist muscle activity during force generation produce specific EMG patterns, which were dependent on velocity, external perturbations, inertial load, and accuracy of a voluntary movement (Gottlieb, Corcos, & Agarwall, 1989a; Meinch, 1984; Sanes & Jennings, 1984). The initial burst of EMG activity has been shown to be unaffected by mechanical perturbations (Hallett & Khoshibin, 1980).

The amount of muscular activity dependents upon both the level of force and the rate of rise of force. Yondenda et al. (1983) evaluated the relationship between the amount of muscular activity and variations in force output. Two characteristics emerged between force production and muscle activity. The amount of muscular activity increased with both increased time to peak force and force output. When the time to peak force was under 150 ms, the amount of muscular activity increased with increasing force levels. However, when the time to peak force was above 150 ms, the amount of muscular activity increased with increasing times to peak force (Yonenda, Oishi, & Ishida, 1983).

The amount of EMG activity has been evaluated in conjunction with the rate of force development over a range of joint angles (Nagasaki, Irie, & Nakamura, 1983). The rate of force development was constant during the first 70 ms over joint ranges of 30° to 120° of elbow flexion. This was evident even though the effective muscular force of elbow extension may be affected at different angles of movement. Changes in timing had no effect on the pattern over which the rate of muscle tension was developed. The amount of discharge during ballistic contractions varied more than during ramp contractions. Perhaps both speed and amount of force may contribute to EMG activity and force relationships.

The different discharge patterns of EMG activity determined by preprogramming may be related to different movement strategies (Nagasaki, Irie, & Nakamura, 1983).

The amount of EMG activity can be influenced by target force. Suzuki, Yamazaki, and Matsunami (1994) evaluated power grip contractions to target forces between 16.7% and 100% of a maximum voluntary contraction (Suzuki, Yamazaki, & Matsunami, 1994). The rate of rise of force along with the amount of EMG activity increased with peak force, while the time to peak force was held constant when contractions were between 16.7% to 50% of a subject's maximum voluntary contraction (Suzuki, Yamazaki, & Matsunami, 1994). When the target forces were 66.7% or greater of a maximum voluntary contraction, the rate of rise of force rise and amount of EMG activity leveled off while the time to peak force was prolonged. However, after 66.7% of a maximum voluntary contraction there was no further increase in EMG activity. This corresponded with the amplitude of EMG activity being modulated up to 50% of a maximum voluntary contraction, while the amplitude of EMG activity leveled off with the duration being modulated above 66.7% of a maximum voluntary contraction.

Contractions of 50% of a maximum voluntary contraction or less were suggested to support the pulse-height model, while contractions greater than 66.7% of a maximum voluntary contraction appeared to support a pulse- width/duration model

(Corcos et al., 1990). Additionally, the initial burst duration of EMG activity were identical for 16% through 100% of a maximum voluntary contraction (Suzuki, Yamazaki, & Matsunami, 1994).

Motor unit recruitment may be indicative of changes in EMG activity and reflect motor programming. Solomonow, Baratta, Shoji, and D'Ambrosia (1990) noted a strong dependence of intramuscularly recorded EMG activity and force production. When force output increased up to 50% of a maximum voluntary contraction, there was a linear relation between intramuscular EMG activity and force output. After 50% of a maximum voluntary contraction the EMG-force curve became progressively non-linear. The data indicated a switch from a linear to a non-linear relationship between EMG activity with increasing force production.

Solomonow (1990) indicated a change in the muscle control strategy can appear around 50% of a subject's maximum voluntary contraction. Additionally, the pattern of motor unit recruitment was shown to be different between muscles, which possibly related to different fiber types (Solomonow et al., 1990). That is, there was a more linear EMG-force curve for slow twitch muscles when compared to fast twitch muscles (Solomonow et al., 1990). Muscle type and the apparent switch in strategies which occurred around contractions that were greater than 50% of a maximum voluntary contraction may confound the evaluation of motor control models.

Additionally, motor neuron pool excitability which has been related to EMG activity, may provide further evaluation into the control of single-joint movements (Butler, Yue, & Darling, 1993).

Motor Neuron Pool Excitability

Control of single joint movements has been described by the dual-strategy hypothesis. This hypothesis proposed different independent variables dictated the different movement strategies as a consequence of changes in the excitation pulse. According to Gottlieb, Corcos, and Agarwall (1989a), this excitation pulse should reflect the status of the excitability of the spinal motor neuron pool.

Motor neuron pool excitability has been assessed by evaluating changes in the Hoffman reflex (H-reflex) (Angel & Hoffman, 1963; Honore, Demaire, & Coquery, 1983; Schieppati, 1987). The H-reflex can been defined as an electrically stimulated monosynaptic reflex which primarily excites the muscle spindle's Ia afferents. Additionally, the overall reflex excitability may be influenced by excitation of Ib afferents from Golgi tendon organs, group II afferents from muscle spindles and larger cutaneous afferents (Schieppati, 1987). The impulses travel to the spinal cord where monosynaptic and pollysynaptic connections cause motor neurons to fire, thereby causing the extrafusal muscle to contract (Honore et al., 1983; Schieppati, 1987).

The validity and reliability of the H-reflex (as a measure of the excitability of the alpha motor neuron pool) has been evaluated by Crayton (1981) and Hugon (1973). Because of the variability of the H-reflex, Crayton (1981) and Hugon (1973) concluded that one test measurement should consist of the average of at least 5 to 7 (and up to 20) H-reflex measurements. Crayton (1981) further demonstrated a wide inter-subject variability in reflex recording; however, there was a small test/retest variability for each individual. Because of this variability, Crayton (1981) suggested that changes in the H-reflex should only be analyzed relative to each subject's baseline reflex (Hoffman, 1973).

Several methods can be used to evaluate changes in motor neuron reflex excitability. The change in excitability has typically been evaluated as a percentage change of the size of the test H-reflex in comparison to a control (baseline) reflex (Hugon, 1973; Schiepatti, 1987). This method of analysis requires an understanding of how changes in stimulus intensity can influence the H-reflex amplitude. As stimulation intensity increased, the amplitude of the H-reflex will follow a bell-shaped curve. That is, the H-reflex will become progressively larger up to a critical point, after which the amplitude gets progressively smaller until the reflex fades away. Therefore, test H-reflex alterations elicited by a given conditioning stimulus depend not only on the conditioning volley, but also on the amplitude of the control test reflex (Crone, Hultborn, Mazieres, Morin, Nielsen, & Pierrot-Deseilligny, 1990). This aspect of H-reflex recruitment makes it difficult to determine the "true" amount of facilitation or inhibition. That is, a small control reflex could result in a large amount of facilitation, while a larger control reflex would result in a smaller amount of facilitation (Crone et al., 1990). Therefore, using percentage change, it may be difficult to estimate the real amount of either excitation or inhibition of the motor neuron pool.

The H/M ratio may be used as an alternate method of analyzing changes in motor neuron reflex excitability . The H/M ratio represents the percentage of the motor neuron pool that may be considered to be active at any particular time. The maximum M-response represents 100% of the activity of the specified muscle's motor neuron pool. The H/M ratio allows a quantification of the percentage of the active motor neuron pool. This interpretation enhances that ability to compare changes in the H-reflex between subjects (Crone et al., 1990). Crone and colleagues (1990) established that regardless of differences in the maximum H-reflex, the change in sensitivity to facilitation followed the same pattern as long as the same control reflex sizes were explored.

The level of maximum voluntary contraction has been shown to affect the H-reflex. Butler, Yue, and Darling (1993) evaluated isometric contractions up to 100% of a maximum voluntary contraction. The H/M amplitude of the soleus muscle was shown to be positively correlated to isometric contractions up to 50% of the maximum voluntary contraction. When the maximum voluntary contraction was 60% or above there was no correlation with force output and the H/M amplitude. In fact, the amplitude of the H-reflex showed no further increase. The H/M ratio was larger during rising rather than falling torque levels.

The relationship between force output and changes in the amplitude of H-reflex may be a result of different methods of motor unit recruitment at different force levels (Butler, Yue, & Darling, 1993). The soleus muscle, when producing a plantar flexion movement with the knee bend, should be considered the prime mover during the response. Therefore, the soleus muscle may be the prime mover up to 50% of a plantar flexion force (Hof & van den Berg, 1977). Up to 50% of a maximum voluntary contraction there was a linear increase in soleus muscle activation. When force output was greater than 50% of a maximum voluntary contraction, the gastrocnemius appeared to have an increased contribution on force output. The soleus motor neurons appeared to be mainly recruited up to 50 to 60% of a maximum voluntary contraction (Butler, Yue, & Darling, 1993).

Motor Neuron Excitability and Force

Changes in motor neuron pool excitability may relate to both force and timing of the movement (Frank, 1986). Butler, Yue, and Darling (1993) established that the amplitude of the H-reflex rose linearly with increased force output. This occurred up to 60% of a maximum voluntary contraction. After 60% of a maximum voluntary contraction, the H-reflex increased in curvilinear fashion. Corcos et al. (1990) indicated that the SS and SI strategies produce different excitation pulses, which should be reflected by changes in EMG activity and limb trajectory. Since the H-reflex rose in a curvilinear fashion after 60% of a maximum voluntary contraction, the relationships between EMG activity and limb trajectory may be compromised with large force productions. In fact, some of the tasks in the isometric study by Corcos et al. (1990) exceeded 60% of a maximum voluntary contraction. This may be a possible explanation for the lack of conclusive results. Further research is indicated to evaluate the relationship between the excitation pulse and EMG activity and peak torque in isometric contractions. The excitation pulse may additionally influence reaction times, which may be fragmented into premotor, motor and movement times.

Reaction Time Fragmentation

The effects of task and stimulus complexity on movement parameters has been analyzed with premotor and movement times during simple reaction time paradigms. Premotor reaction time has been defined as the time from stimulus onset until onset of EMG activity. This period represents stimulus identification, response selection, and the transfer of the motor program to the appropriate muscle for movement execution (Schmidt, 1988). Motor time can be defined as the interval between the onset of EMG activity to initiation of the response which reflects the execution of the motor program (Eichenberger & Ruegg, 1984; Schmidt, 1988).

An increase in spinal excitability has been shown prior to the rapid generation of plantar flexion torque. This change has been used to further fragment premotor time into two separate intervals (Eichenberger & Ruegg, 1984). The first interval (I_1) was from the stimulus presentation until the onset of H-reflex facilitation. This interval may represent stimulus processing and response selection stages. The second interval (I_2) was from H-reflex facilitation until onset of EMG activity. This interval should reflect preparation of the motor system prior to movement execution. Any differences between these two intervals during different tasks should allow one to determine whether a change in programming or movement execution occurred (Eichenberger & Ruegg, 1984). These intervals were derived from changes in spinal facilitation which occurred prior to EMG activity in voluntary movement.

Spinal Facilitation

Sullivan (1980) ascertained that the increase in spinal excitability occurred 40 ms prior to soleus EMG activity, while Mitchie et al. (1976) reported this increase some 90 ms to 120 ms prior to overt movement or 50 ms to 80 ms prior to EMG. According to Mitchie et al. (1976), the onset of spinal facilitation was time-locked to the onset of EMG and not to an initiation signal. That is, regardless of reaction time, the facilitation of the H-reflex always occurred within the 50 ms to 80 ms window prior to the onset of EMG activity. For reaction time tasks, more recent reports have confirmed these data (Brunt & Robichaud, 1996; Eichenberger & Ruegg, 1984; Ruegg, Krauer, & Drews, 1990; Riedo & Ruegg, 1988).

These findings appear to be in conflict with Frank (1986), who reported that reflex facilitation was not time-locked to onset EMG but rather can be influenced by a subjects' preparatory set and duration of reaction time. The timing of reflex stimulation was shown to change in an anticipation timing task (Frank, 1986). In this case, the onset of facilitation was significantly earlier in relation to EMG activity onset for a coincident timing task than for a simple reaction time task. According to Gottlieb and colleagues (1989a) classification of movements based upon the independent variables, this task would appear to be classified as an SI strategy. That is, a coincident timing task focuses on timing, not speed of the movement. Accordingly, this task would modulate the duration of the excitation pulse and agonist EMG activity bursts and inertial torques should rise at a uniform rate, independent of the movement speed. Frank's (1986) study seemed to support an increase in the pulse width (e.g. SI strategy). The timing of the reflex facilitation possibly reflected movement preparation. That is, movements that demand more precision (coincident timing versus simple reaction time) may require greater preparation time (increased pulse duration) between onset of reflex facilitation to premotor time.

The relationship between amplitude changes of the reflex facilitation may reflect an SS strategy which regulates pulse-height. This would account for the difference in Eichenberger and Ruegg’s (1984) findings, in which shorter reaction times were associated with a greater amount of reflex facilitation. This would be attributed to these tasks being carried out using an SS strategy, while longer reaction times may have defaulted to the SI strategy. This could have been a complication of the actual design of the study. Even Eichenberger and Ruegg (1984) indicated that subjects may have used different movement strategies to perform the tasks.

The ability to differentiate the premotor period according to movement preparation allows the analysis of the motor set for a particular movement. The motor set implies the readiness of the central nervous system to implement a planned motor action (Brooks, 1986). For example, an increase in the period from reflex facilitation to onset of EMG activity could reflect a movement that requires precision of execution (Frank, 1986), whereas an increase in the premotor period prior to reflex facilitation could imply increased complexity in movement organization.

Motoneuron Reflex Excitability (Pulse-Width vs Pulse-Height)

Motor neuron pool excitability has been shown to increase prior to the generation of plantar flexion torque (Brunt & Robichaud, 1996; Kagamihara, Komiyama, Ohi, & Tanaka, 1990; Mitchie, Clarke, Sinden, & Glue, 1976; Sullivan, 1980). This increase occurred 50 ms to 80 ms prior to EMG activity onset in a non-choice ballistic task and has been shown to be time-locked to the onset of the EMG activity (Brunt & Robichaud, 1996; Kots, 1977; Mitchie et al., 1976). This period of spinal cord facilitation implies the readiness of the central nervous system to implement the planned motor action (Brooks, 1986; Frank, 1986). If the excitation pulse reflects spinal excitability, then changes in this period of spinal facilitation should correspond to changes in task or instructional variables.

There appears to be support for different task or instructional variables being reflected by changes in spinal cord excitability. The dual-strategy hypothesis proposed that the SI strategy should be modulated by changing the timing (pulse width) of spinal cord facilitation. Kagamihara and colleagues (1990) evaluated the time course of spinal facilitation in a ramp plantar flexion task. In the ramp task, the subject moved at a preselected cursor speed. The onset of spinal facilitation occurred at 92 ms prior to EMG onset during the ramp task. Additionally, during an anticipation timing task there was a lengthening of the time period of spinal cord facilitation (70 ms prior to EMG onset) (Frank, 1986). The dual-strategy hypothesis proposed that the excitation pulse in an anticipation timing or ramp tasks should be classified as an SI strategy because timing and not speed was the dominate aspect of these tasks. Therefore, both of these examples appear to support pulse-width modulation of spinal cord facilitation.

Since speed was the dominate feature of the ballistic and step tasks, they would be classified as SS according to the dual-strategy hypothesis. Kagamihara and colleagues (1990) evaluated the time course of spinal facilitation in a step plantar flexion task. In this task, the subject was requested to reach a target that was designated between 20% to 40% of a maximum voluntary contraction. Spinal facilitation occurred at 55 ms prior to EMG activity onset during the step task.

Numerous studies have established the onset on spinal facilitation to occur between 55 ms to 80 ms prior to EMG onset in ballistic plantar flexion tasks. However, shorter reaction times have greater amounts of spinal facilitation (Eichenberger & Ruegg, 1984). An analysis of this study showed a discrepancy in the time period of facilitation. That is, the period of facilitation for the short reaction times was 90 ms, while this time period was 180 ms for the longer reaction times. This appears to support the assumption that the short and long reaction times may have been carried out under different strategies, an observation which was supported by Eichenberger and Ruegg's (1984) suggestion that these differences may relate to different movement strategies. However, no study has been designed to analyze SS or SI strategies (e.g., pulse-width or pulse-height modulation) and modulation of spinal facilitation. In addition to different movement strategies, the amount of spinal facilitation may also be influenced by force production (Butler, Yue, & Ohi, 1993).

H-reflex Facilitation, Force and Reaction Times

According to Frank (1986), the degree of reflex facilitation may not only be related to timing of the movement but also to force and rate of force production.

Baba and Marteniuk (1983) identified a potential methodological problem in that allowing both peak force and time to peak force to randomly vary could well confound interpretation of the data. Previous studies indicated that the time needed to execute a movement can be influenced by both of these variables (Kawabe-Himeno, 1993; Ito, 1990, 1991; Meyer, Smith, & Wright, 1982).

The relationship between peak force and rate of rise of force has been described by the impulse variability model to the extent that when one variable was regulated, the other variable was proportionally rescaled (Brooks, 1986; Meyer et al., 1982). Although Eichenberger and Ruegg (1983) analyzed the relationship between the size of the H-reflex and movement time and amplitude, they reported inconsistent data for four subjects. These individual differences could well be due to different movement strategies. That is, did their subjects regulate peak torque or time to peak torque? Further research is indicated to determine the relationship between motor neuron excitability and different types of voluntary movements.

Summary

Single-joint isotonic movements can be classified according to the dual-strategy hypothesis. There is some ambiguity as to the ability of this hypothesis to be extended to isometric movements. The dual-strategy hypothesis proposes that movement control can be determined by the nature of the orientation of the instructions to perform a task. Different instructions may control movements by influencing the excitation pulse. This pulse, which may modulate spinal excitability, should be reflected by changes in the H-reflex. My study will examine isometric movements to determine if the dual-strategy can be expanded to account for these movements. The proposed neural mechanism (spinal excitability), that may govern the different strategies, will be evaluated.

CHAPTER 3
METHODS

Participants

Participants included 14 healthy individuals (8 males and 6 females) over the age of 18 years, who had no history of lower extremity disorders that would affect their participation in this study. However, only 11 participantss were included in the analysis. One participant was excluded because of inconsistent H-reflex responses, one due to nonequal pre and post maximum M-responses and one since the M-responses were inconsistent during testing. All participants had normal or corrected-to-normal vision and were asked to refrain from caffeine and alcohol 12 hours prior to the study (Eke-Okoro, 1982). Each participants dominate leg, which was designated as the preferred kicking leg, was tested.

Participants were recruited from colleagues, friends, and students from the Departments of Physical Therapy and Exercise and Sport Sciences. Self disclosure was utilized when determining if a participant met criteria for selection. All participants signed an informed consent form prior to testing (See Appendix A). IRB approval was obtained prior to testing (See Appendix B). All testing took place in the Physical Therapy Motor Behavior lab.

Selection of Force Levels and Bandwidths

In a previous study, participants performed isometric plantar flexion contractions of 20, 40 and 60% of a MVC (Monohar, Brunt, & Robichaud, In Review). In this isometric condition, changes in MVC were equated to changes in distance utilized in the movement tasks. Isometric contractions were performed to bandwidths of 4, 8, 12, 16 and 20% of a participant's MVC. Results showed that participants utilized an SS strategy between the 8% and 12% bandwidths, while using an SI strategy within the larger bandwidths. Figure 3-1 illustrates a 40% MVC where the initial slope of force was similar for both the 4% and 8% and the 12%, 16% and 20% bandwidths. The switch between strategies was shown to occur between the 8% and 12% bandwidths. These results were also consistent for the 20% and 60% force level. Additionally, participants were shown to adopt an approximation of an SI strategy when they were instructed to use different percentages of a MVC to reach the same target bandwidth, which is shown in Figure 3-2. This figure demonstrates that the initial slope of force was similar when moving to the 8% bandwidth for the 20%, 40% and 60% force levels. These results were also consistent for the 12%, 16% and 20% bandwidths.

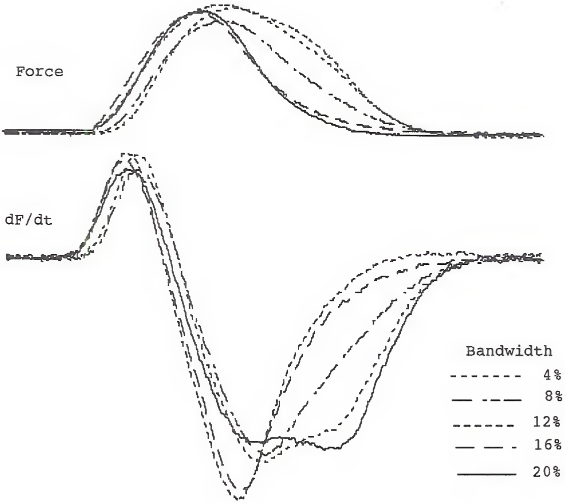


Figure 3-1. These traces represent an individual subject's response to a 40% force level to five different bandwidths.

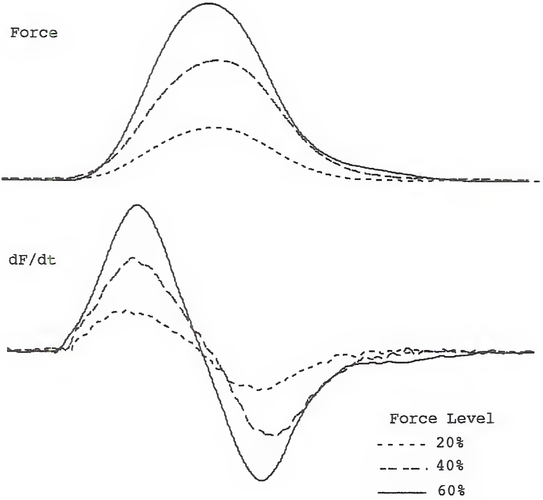


Figure 3-2. These traces represent an individual subject's response to an 8% bandwidth at three different force levels.

The results of the above study were utilized to select the force levels and bandwidths for the current study. Twenty-five percent and 50% force levels were selected since no difference was noted in the initial EMG burst (Q_{30}) when going to the same bandwidth, but moving between the 20%, 40% and 60% force levels. The 5% and 15% bandwidths were selected since a clear difference was observed in the initial slope of force between the 8% and 12% bandwidths.

Instrumentation

EMG

Electromyographic activity was recorded using surface electrodes on the dominate leg. The recording electrodes consisted of two silver-silver chloride electrodes 1 cm in diameter embedded in an epoxy-mounted preamplifier system (amplification x35) (Therapeutics Unlimited), the centers of which were 2 cm apart. A reference electrode was attached on the anterior surface of the tibial crest. The EMG signal was high (4,000 Hz) and low (20 Hz) pass filtered. The frequency response of the EMG signal was between 20 Hz to 4,000 Hz with the low-pass filter time constant being set at 2.5 ms. The signal was further amplified to give a final amplification between 5k to 10k. The processed signal was sampled on-line via an analog to digital converter (Biopac Systems Inc.) at 1000 samples per second for 2 minutes.

Surface electrodes were placed over the soleus, gastrocnemius, and anterior tibialis muscles of the dominate leg. Soleus muscle activity was recorded over the dorsal medial surface of the posterior calf, inferior to the muscle belly of the gastrocnemius (Maryniak & Yaworski, 1987). Gastrocnemius activity was recorded over the muscle belly of the gastrocnemius on the posterior calf, while tibialis anterior activity was recorded over the muscle belly of the tibialis anterior on the anterior/lateral portion of the upper calf (Cram, 1991).

Stimulation

H-reflexes were elicited using an isolation unit attached to a Grass 44 stimulator. A one ms rectangular pulse was used to elicit stimulation. A ground electrode was placed under the stimulated thigh. All data was sampled on-line and stored on an external drive for further analysis.

Force Transducer

A gensico cell load with a range from 0 to one hundred pounds of force was utilized. Force output was measured in voltage and then converted to both the percentage of the participant's maximum voluntary contraction and then Newtons for data analysis. The measure of Newtons was derived from converting volts into pounds and then multiplying this figure by the constant of one pound equaling 4.44 Newtons.

Participant Positioning

Participants were seated in a modified chair, as depicted in Figure 3-3, which had attached leg and head rests. A device was attached to the chair that, regardless of leg length, maintained the participant's hip in 90° of flexion, knee in 120° of flexion, and ankle positioned at neutral (Hugon, 1973). The participant was positioned in the chair with his/her back resting against the chair, arms folded across his/her lap and the head positioned on a head rest designed to eliminate head movement. The tested thigh was secured to the chair by straps that were placed over the medial and distal portions of the femur. The foot was secured in an ankle high wire-foam binding which was secured to a wooden board. Underneath the wooden board, at the level of the metatarsal heads, a force transducer was positioned to measure the force produced during voluntary isometric plantar flexion.

Testing Sessions

Participants were asked to perform isometric plantar flexion movements at two specified force levels to two specific bandwidths. Two separate studies were conducted with participants being tested on two separate days. Each day they completed half of the protocol for each of the

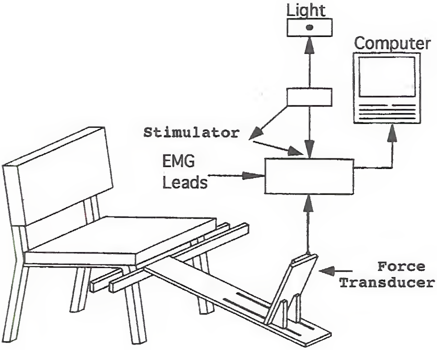


Figure 3-3. Design of Experimental Set-up.

studies. That is, one day involved the analysis of isometric contractions performed to either 25% or 50% of a participant's maximum voluntary contraction. The second day involved the same analysis; however, the other force level was tested. These contractions were performed to bandwidths of 5% and 15% of the specified force level. The order of force levels (e.g., 50% and 25%) and bandwidths (e.g., 5% and 15% of the specified force level) was randomized to prevent any order effects.

Procedures

Study 1

Participants were instructed to perform 10 maximum isometric plantar flexion contractions. The average of these contractions was used to calculate each participant's maximum voluntary plantar flexion contraction. Preselected percents (25% and 50%) of maximum voluntary contraction were calculated. Two bandwidths (5% and 15%) of the preselected percent maximum voluntary contraction were calculated. Reference lines corresponding to the specified bandwidth were shown on the computer screen. For example: The participant may have been asked to push down with an isometric contraction that was 25% of his or her maximum voluntary contraction within a 10% range. Therefore, reference lines would be indicated at the levels of 20% and 30% of maximum voluntary contraction.

Testing began with learning trials to familiarize the participant with the testing procedure, task, and equipment. Participants practiced matching isometric plantar flexion contractions to the specific force level (25% or 50% of their maximum voluntary contraction). Concurrent feedback was used by having them view, in real-time, their force output on a 35.56 cm computer screen placed 60 cm at eye level in front of them. Output from the force transducer was sampled on-line on a computer screen and recorded for further analysis. After 50 trials the participant was asked to complete 10 additional trials. If 80% of the trials matched within the target bandwidth, the participant was considered to have learned the task and testing was initiated. During testing, participants received concurrent feedback. Additionally, these trials were used to calculate a participant's average premotor time for each specified force level.

A 5 mm red light emitting diode (intensity 30 to 40 mcd) was situated 60 cm in front of the participant. This was used as an initiation signal. Participants were instructed that following a red light signal to isometrically plantar flex their foot, which moved a cursor that measured force output on the computer. Participants were asked to perform isometric contractions to each specified force level (25% and

50% of the maximum voluntary contraction) to two target bandwidths (5% and 15% of the specified force level).

Participants did not exhibit any background EMG activity. This was monitored on-line. Trials were repeated when a participant did not achieve the criterion force within the designated bandwidth. Participants were eliminated from the study when less than 80% of their trials did not met the specified criteria. No participant was eliminated from the study due to not meeting the above criteria.

Study 2

The same protocol was followed in Study #2 as in Study #1, with the exception that H-reflexes were recorded during the testing session. The H-reflex was recorded from the surface electrode placed over the soleus muscle. One ms stimulations were applied to the skin over the tibial nerve in the popliteal fossa. Proper cathode placement was determined when 1) the direct motor reflex (M-wave) and Hoffman reflex (H-wave) displayed similar wave configurations, 2) the H-reflex was evoked before the M-reflex, and 3) the least amount of current was required to elicit a H-reflex. The stimulating intensity was increased until a maximum M-responses were observed, after which the average of 10 M-responses were calculated. The intensity was decreased until a 30% H-reflex, relative to the maximum M-response was obtained. This was the stimulating intensity for the study. Ten baseline H-reflexes were recorded prior to testing.

Each participant completed six blocks of 15 trials which included tibial nerve stimulations that were 15, 30, 45, 60, 75 and 90 ms prior to the recorded average premotor time for the specified force level. The intervals within each trial block were randomized. A variable rest period of between 5 to 10 s was used between trials. After the trial blocks were completed, 10 maximum M-responses were again obtained.

Design and Analysis

The Acknowledge software program was utilized for data collection and analysis.

Study 1

The dual-strategy hypothesis was evaluated to determine if it could be extended to single-joint isometric movements. The dual-strategy hypothesis states that isotonic movements can be classified according to either a SS or SI strategy. The hypotheses tested was that single-joint isometric movements can be classified according to SS and SI strategies.

Dependent variables included the average of 7 trials for peak force, and the magnitude of the soleus EMG response (integral of the rectified signal). Soleus EMG activity included the first 30 ms of activity and the activity from initiation until peak velocity. For data analysis, these values were normalized to the integral of a 100 ms maximum voluntary soleus contraction. All of these values were first divided out by there respective time. For example, the normalized value for Q_{30} was obtained by the formula (integral for Q_{30}/30 ms) /(integral for 100 ms of MVC/ 100 ms) X 100. The final value obtained indicated the percentage of maximum of soleus EMG activity present. Additionally, the first time derivative of force which included 1) peak of the first time derivative (force-time velocity), 2) the time until peak velocity, and 3) the slope of the force-time velocity curve. Independent measures were bandwidths and force level. A 2 X 2 (Force X Bandwidth) repeated measures design ANOVA was used to compare differences among the test conditions on each dependent measure. All levels of significance was designated at $p < 0.05$. A Super ANOVA statistical program was used for data analysis.

Study 2

Different movement strategies were proposed to produce different neural excitation pulses. This neural pulse may be reflected by changes in motor neuron reflex excitability. The hypotheses tested was that single-joint isometric movements performed under the SS and SI strategies produced different intensities and patterns of motor neuron reflex excitability prior to EMG activity onset.

The dependent measures were the peak of spinal facilitation at the onset of EMG activity, onset of change in spinal excitability, and the final slope of spinal facilitation. The onset of change in spinal excitability was determined by the time of the first data point which was one standard deviation above the baseline average. Changes in the H/M ratio were used to calculate the dependent measures. The H/M ratio was calculated from the ratio of the respective (test) H-reflex to the average maximum M-response. The maximum M-response was the average of 10 responses. The H/M ratio was ranked in ascending order from the time of the elicited H-reflex to the onset of soleus muscle activity. Once these ordered responses were rank ordered, a running average over 10 consecutive reflexes was calculated. That is, the average ordered trials 1 to 10 constituted the first value, while the second value was the average of trials 2 to 11. This running average was calculated for all the ordered H/M ratios for each force level and bandwidth. Using the running average, the dependent measures (slope, time and peak facilitation) were calculated for each force level and bandwidth.

Independent measures were specified force levels (25% and 50%) and bandwidths (5% and 15% of the specified force). A 2 X 2 ANOVA was used to determine any differences between the duration of change in spinal excitability, final slope of spinal facilitation, and the peak amplitude of the H/M ratio at the onset of EMG activity as related to force levels and bandwidths. All level of significance was designated at $p < 0.05$. A Super ANOVA statistical program was used for data analysis.

CHAPTER 4
RESULTS

The dual-strategy hypothesis was evaluated to determine if it could be extended to include single-joint isometric contractions. The hypotheses tested were that single-joint isometric contractions can be classified according to SS and SI strategies. Dependent variables selected to differentiate movement strategies were the peak of the first time derivative of force (dF/dt), slope and time to peak dF/dt, initial slope of force until peak dF/dt, slope and time to peak force, and Q_{30} and Q_{acc} of soleus EMG activity. Independent measures were bandwidths (5% and 15%) and force levels (25% and 50%). A 2 X 2 (Force X Bandwidth) ANOVA design with repeated measures was used to compare the differences among the test conditions on each dependent measure.

This chapter is presented in the following sequence. First, data for Study 1 is presented according to the following subheadings: temporal measures, slope of dF/dt and the slopes of force, soleus EMG activity, and the peak of the first time derivative of force. These data are followed by a short summary section that ties these results to the hypotheses. The results of Study 2 are presented in the following manner: introduction, time of premovement facilitation, slope of premovement facilitation, and peak of premovement facilitation. This section ends with a summary of how these results fit with the stated hypotheses.

Study 1

Temporal Measures

There was a Bandwidth main effect for both time to peak dF/dt and time to peak force [$\underline{F}_{1,10} = 9.32$, $\underline{p} \leq 0.01$ and [$\underline{F}_{1,10} = 5.4$, $\underline{p} \leq 0.01$]. As expected, the time to peak dF/dt and the time to peak force increased with the smaller bandwidth. The mean data, shown in Figure 4-1, reveals the time to peak dF/dt decreased from 70 ms for the 5% bandwidth to 63 ms for the 15% bandwidth. Similarly Figure 4-2 illustrates that mean data for the time to peak force took an average of 179 ms to reach the 5% bandwidth, while the time to reach the 15% bandwidth decreased to 134 ms. It appears that the time increases for the 5% bandwidth in order for the participant to comply with the instruction to be "fast and accurate".

Similarly, for the time to peak dF/dt there was a main effect for Force [$\underline{F}_{1,10} = 10.95$, $\underline{p} \leq 0.01$]. As predicted, the time to peak dF/dt was greatest for the largest force (50% MVC) and the smallest bandwidth (5%). Figure 4-1 depicts the mean data for the time to peak dF/dt for the 25% force level was 55 ms, while the 50% force level was 77 ms.

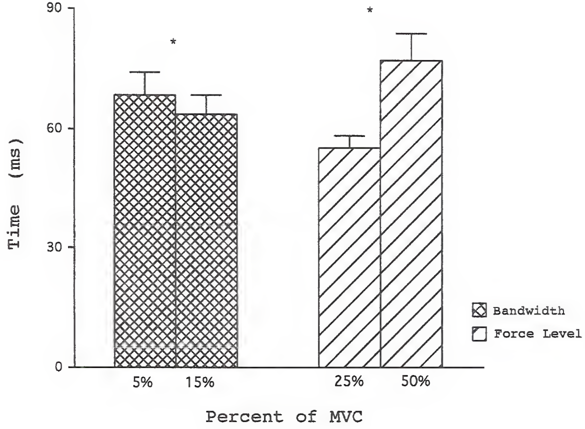


Figure 4-1. Mean data (+SEM) for the time to peak dF/dt for main effects of Force and Bandwidth.
* $p \leq .05$.

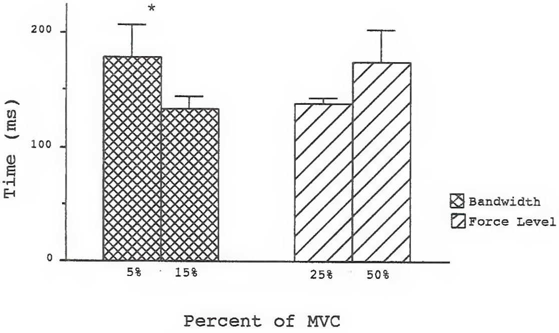


Figure 4-2. Mean (±SEM) data for the time to peak force for main effects of Bandwidth and Force.
* $p \leq .05$.

There was no difference between the force levels for the time to peak force [$\underline{F}_{1,10} = 2.08$, $\underline{p} = 0.17$], which implies participants held force rise time invariant (see Figure 4-2). The mean data revealed the time to peak force increased from 138 ms for the 25% force level to 174 ms for the 50% force level. Upon closer inspection of the data, the time to peak force appeared to be most influenced by the bandwidth. That is, between the 25% and 50% force level, there was a 60 ms difference for the 5% bandwidths, while between the 15% bandwidths there was only a 25 ms difference. This implied that when the bandwidth became large enough to no longer affect the speed of the movement, changes in the level of force only minimally affected movement time. Gordon and Ghez (1987) presented similar results and suggested that participants regulated (kept fairly constant) the time to peak force while controlling (allowed to vary) the rate of rise of force. This strategy of movement was termed pulse-height control.

Slope of dF/dt and the Slopes of Force

There was a Bandwidth main effect for initial slope of force ($\underline{F}_{1,10} = 8.7$, $\underline{p} < 0.05$) and slope to peak force ($\underline{F}_{1,10} = 10.6$, $\underline{p} < 0.05$). Mean data for the initial slope of force, shown in Figure 4-3, for the 5% bandwidth was 1075 N/sec, whereas the slope increased for the 15% bandwidth to 1301

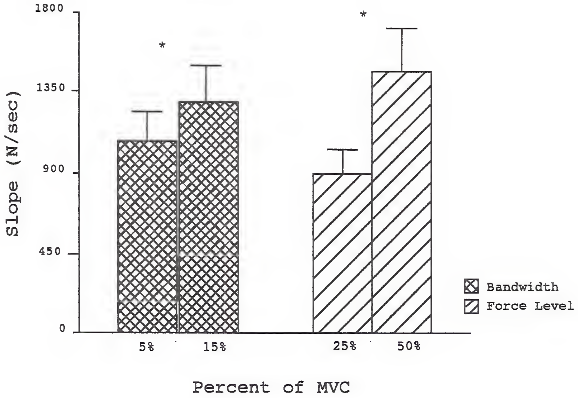


Figure 4-3. Mean (±SEM) data for the initial slope of force for main effects of Bandwidth and Force.
* $p \leq .05$.

N/sec. In Figure 4-4, the slope to peak force illustrates similar findings. Here the mean data for the 5% bandwidth was 820 N/sec, while the 15% bandwidth was 1047 N/sec. These data verified that in order to be accurate, participants decreased the rate of rise of force with a corresponding decrease in bandwidth. These findings are further confirmed when viewing individual participant data. When we compared the eleven paired individual participant trials for each bandwidth (total of twenty-two pairs of trials), only one participant's trials for the 5% demonstrated trajectories which rose along the same trajectory. Figures 4-5 and 4-6 illustrate that the slope of force rose along different trajectories when the participant moved between the 5% and 15% bandwidths for the specified force level.

There was a main effect for Force for both the initial slope of force [$\underline{F}_{1,10} = 11.9$; $\underline{p} \leq 0.01$] and slope to peak force [$\underline{F}_{1,10} = 12.7$, $\underline{p} \leq 0.01$]. As shown in Figure 4-3, mean data for the initial slope of force on the 25% force level was 684 N/sec, whereas the slope increased for the 50% force level to 1180 N/sec. Similar findings were established for the slope to peak force (see Figure 4-4). That is, there was a greater rate of rise of force to the greater force level.

For the slope to peak dF/dt, there was a significant main effect for Bandwidth ($\underline{F}_{1,10} = 15.6$, $\underline{p} \leq 0.05$). Mean data for the slope of dF/dt on the 5% bandwidth was 2.4 KN/sec,

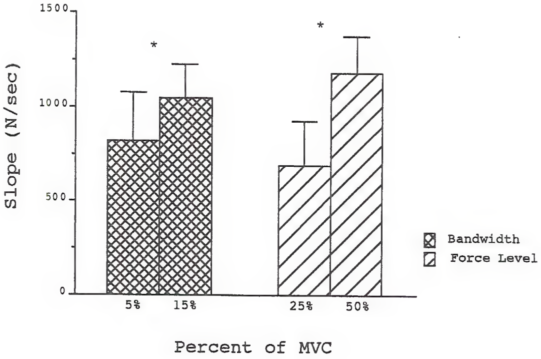


Figure 4-4. Mean (±SEM) data for the slope to peak force for main effects of Bandwidth and Force.
* $p \leq .05$.

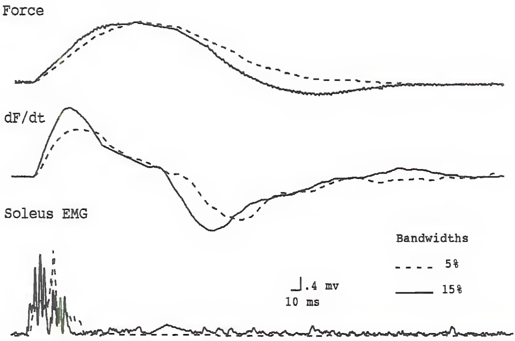


Figure 4-5. These traces represent an individual subject's response to the 25% force level for the 5% and 15% bandwidths.

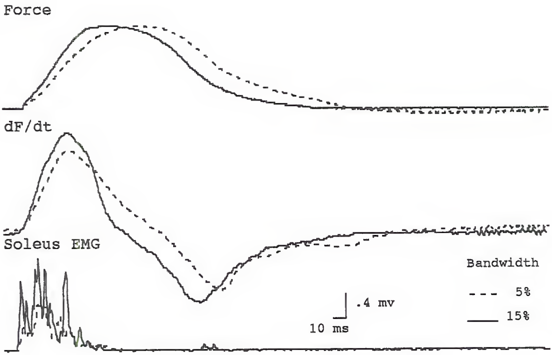


Figure 4-6. These traces represent an individual subject's response to the 50% force level for the 5% and 15% bandwidths.

whereas the slope to the 15% bandwidth was 3.1 KN/sec. Participants increased the slope of dF/dt when moving to the larger bandwidth, which is depicted in Figure 4-7. The absolute difference for the slope to peak dF/dt between force levels and bandwidths were similar, however, the ANOVA failed to reach significance for force levels. The mean data demonstrates this similarity, since for the slope to peak dF/dt for the 25% force level was 2.4 KN/sec, whereas the slope for the 50% force level was 3.2 KN/sec. Thus, in absolute numbers, there was a larger difference for the slope to peak dF/dt between the force levels when compared to the bandwidths, which is represented in Figure 4-7. The lack of a significant effect for force level was probably due to the large standard deviation. Additionally, individual examination of the data for the slope to peak dF/dt revealed that only 37% of the (3 out of 11) participants adopted a policy where movement trajectories rose along the same pathway (see Figures 4-8 and 4-9).

Peak of the First Time Derivative of Force (dF/dt)

There was a main effect for both Force ($\underline{F}_{1,10} = 9.6$, $\underline{p} \leq 0.01$) and Bandwidth ($\underline{F}_{1,10} = 8.9$, $\underline{p} \leq 0.01$) for the peak of dF/dt. Participants generated a larger peak dF/dt when going to the 50% force level (mean data for the 25% force = 1084 N, 50% force = 1670 N). The same finding occurred when going to

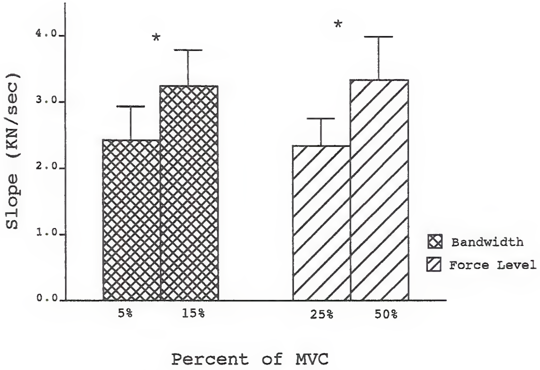


Figure 4-7. Mean (+SEM) data for the slope to peak dF/dt for main effects of Bandwidth and Force. * $\underline{p} \leq 0.05$.

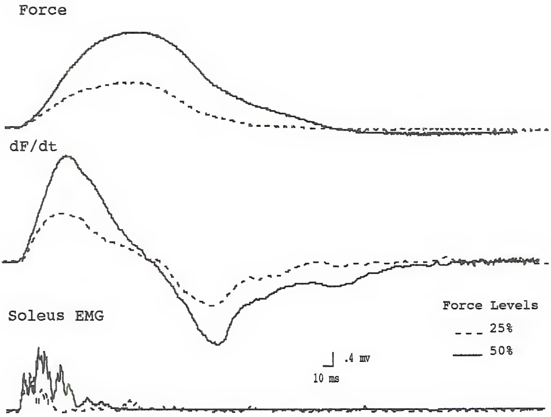


Figure 4-8. These traces represent an individual subject's response to the 5% bandwidth for both the 25% and 50% force levels.

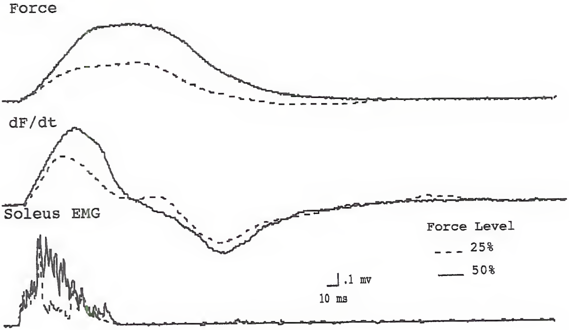


Figure 4-9. These traces represent an individual subject's response to the 15% bandwidth for both the 25% and 50% force levels.

the 15% bandwidth (mean data for the 5% bandwidth = 1260 N, 15% bandwidth = 1494 N). That is, participants initially generated a greater peak dF/dt to both the larger bandwidth and force level.

Soleus EMG Activity (Q_{30} and Q_{acc})

For Q_{30} of the soleus EMG activity there was a main effect for Bandwidth ($F_{1,10} = 9.7$, $p \leq 0.01$). Participants initially utilized 14.2% of MVC when moving to the 5% bandwidth, whereas 18% of MVC was activated for the 15% bandwidth (see Figure 4-10). Individual participant data confirmed, when moving between the 5% and 15% bandwidths for the specified force level, that for soleus EMG activity there was a clear difference in the integral (see Figures 4-5 and 4-6).

For Q_{30} there was no Force main effect. Participants utilized approximately 15.3% of a MVC when moving to the 25% force level, whereas 16.8% of a MVC was activated for the 50% force level. Figure 4-10 clearly depicts no change when the force level was increased. This finding was supported by analyzing individual data. Figures 4-8 and 4-9 clearly showed that the integral of soleus EMG activity was the same when the force level was changed. This finding indicated that Q_{30} was invariant to changes in force. According to

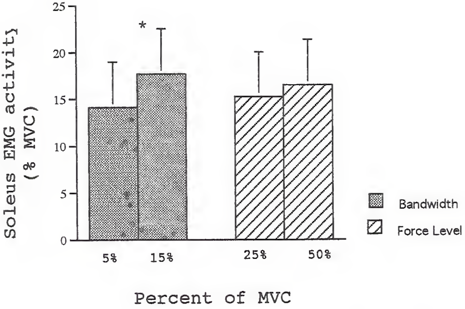


Figure 4-10. Mean (+SEM) data for soleus EMG activity for the time period of Q30 for main effects of Bandwidth and Force.
* $\underline{p} \leq 0.05$

Corcos et al. (1990) this finding would be in accordance with the usage of an SI strategy.

There was a significant interaction between Force and Bandwidth ($\underline{F}_{1,10} = 5.89$, $\underline{p} \leq 0.01$) for Q_{acc}. Mean contrasts ascertained that the interaction occurred because there was no difference between the bandwidths for the 25% force. All other mean contrasts produced a difference between both force level and bandwidth. As expected, there appeared to be an increase from the lower to the higher force level and smaller to larger bandwidths which is depicted in Figure 4-11.

Summary of Results--Study 1

Same Force Level--Different Bandwidths

According to Hypothesis #1 it was expected that the variables of slope and peak of dF/dt in single-joint isometric contractions would all rise along different trajectories between the 5% and 15% bandwidths. Additionally, both Q_{30} and Q_{acc} were expected to positively rise with increased bandwidth. This was supported by the Bandwidth main effects for time to peak dF/dt, time to peak force, both the slope of dF/dt and the initial slope of force peak of dF/dt, and Q_{acc} and Q_{30} of the soleus EMG activity. Participants decreased the rate of rise of force with a corresponding decrease in bandwidth presumably in order to be

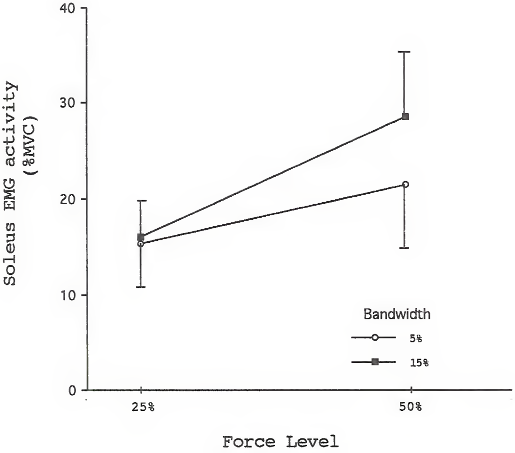


Figure 4-11. Mean (+SEM) data for Qacc for soleus EMG activity for the 25% and 50% force levels.

accurate. Additionally, it was suggested that Q_{acc}, slope and peak of dF/dt would be larger for the 50% force level when compared to the 25% force level. This was supported by the Force main effects for these variables. Upon analysis of the mean data, these variables for the 25% force level were smaller than the mean data for the 50% force level. The results support Hypothesis #1 along with corresponding usage of an SS strategy.

Different Force levels--Same Bandwidth

According to Hypothesis # 2, the variables of slope to peak dF/dt and the initial and full slope of force in single-joint isometric contractions would all rise along the same trajectory between the 25% and 50% force levels. Additionally, Q_{acc} should positively increase to the larger force level, while Q_{30} should remain invariant. The results of this study did not fully support this research hypothesis. There were Force main effects for force for the time to peak dF/dt, both the initial slope and full slope to peak force, the peak of dF/dt, and Q_{acc} of EMG activity. This indicated initial and full slope of force did not rise along the same trajectory and that a greater rate of rise of force was generated for the greater force level. There was no main effect for the slope to peak dF/dt, however this lack of significance was probably due to the large standard deviation. Additionally, Q_{30} was hypothesized to be invariant with changes in MVC, which was supported. This data did not support a pure SI strategy.

Study 2

The dependent variables that were selected to compare changes in motor neuron pool excitability and the parameters of the isometric contraction were time of facilitation prior to soleus EMG activity, slope of facilitation and the peak facilitation at the onset of soleus EMG activity. The independent variables were bandwidth (5% and 15%) and force level (25% and 50%). A 2 X 2 (Force X Bandwidth) ANOVA design with repeated measures was used to compare mean differences among the test conditions on each dependent measure.

To ensure the stimulating and recording conditions did not change during the testing session, pre and post maximal M-responses were evaluated. There was no difference between these responses which indicated that the testing conditions remained constant. The stability of each trial was indicated by low correlations between the test M-response and time. Regression analysis for each participant (eleven) over each test condition (four) revealed only low correlations between the M-response and time. The correlation coefficient values ranged from 0.08 - 0.32 ($\underline{M}$ = .19), which indicated stability of the M-response. Figure 4-12 illustrates a typical participant's M-response over one test condition (movement to a 5% bandwidth at a 25% force level).

For the baseline level of motor neuron pool excitability, there was no Force or Bandwidth main effect (see Figure 4-13). Baseline level of excitability was defined as the level of motor neuron pool excitability that was present prior to H-reflex facilitation. The duration of baseline activity was typically between 75 to 100 ms. The baseline level of soleus muscle that was activated ranged from 28% of M-max for the 25% force level to 31% of M-max for the 50% force level. A typical participant's response to each test condition is depicted in Figures 4-14 and 4-15. Additionally, Table 4-1 displays the data for each individual subject for each test condition.

Time of Facilitation

The time of premovement facilitation of the motor neuron pool was the time when the motor neuron pool exceeded two standard deviations above the baseline level of excitability until the onset of soleus EMG activity. There was Bandwidth main effect for the time of facilitation for the H/M ratio ($\underline{F}_{1,10}$ = 21.2, $\underline{p} \leq 0.01$). Figure 4-16 illustrates that the time of facilitation was longer for the 5% bandwidth

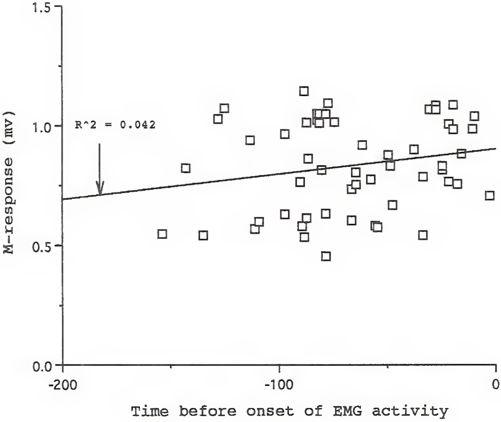


Figure 4-12. This scattergram represents an individual subject's change in the M-response over time.

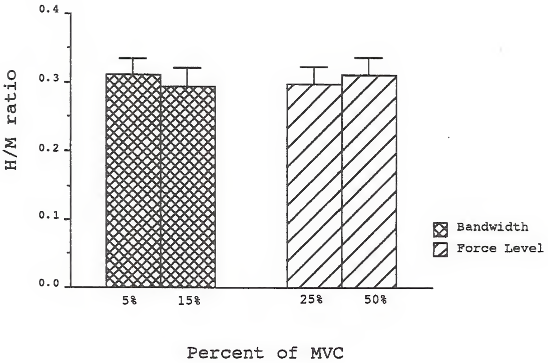


Figure 4-13. Mean (±SEM) data for the baseline level of spinal excitability prior to the onset of soleus EMG activity.

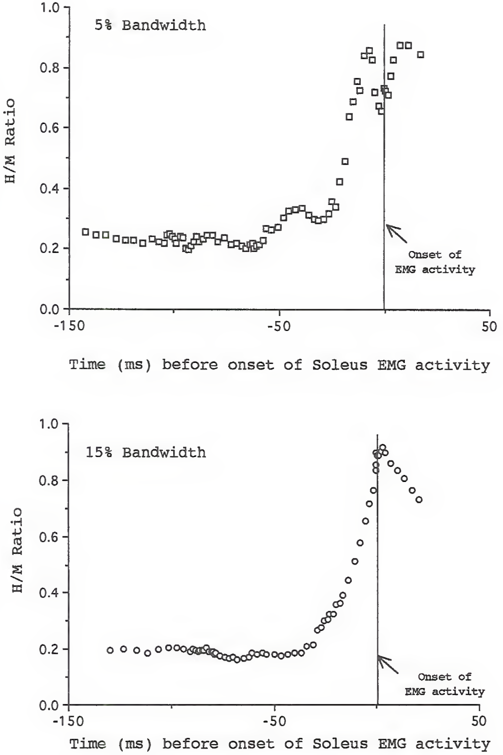
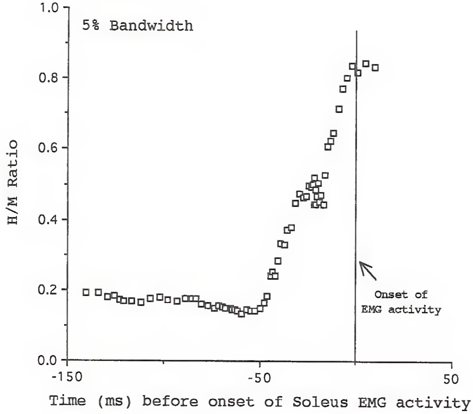


Figure 4-14. These graphs represent an individual subject's change in spinal excitability prior to EMG onset to a 25% isometric contraction.



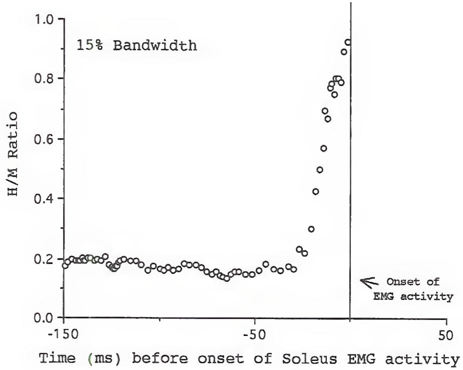


Figure 4-15. These graphs represent an individual subject's change in spinal excitability prior to EMG onset to a 50% isometric contraction.

Table 4-1

Individual Data for the Effects of Force Level and Bandwidth for the Time, Slope, and Peak of Premovement Facilitation.

Subject	Source	Force Level			
		25%		50%	
		Bandwidth			
		5%	15%	5%	15%
1	Time (ms)	49.70	51.50	23.00	22.80
	Slope %/sec	.79	1.12	2.41	4.03
	Peak H/M ratio	.90	1.12	1.02	1.34
2	Time (ms)	48.50	26.00	20.00	17.40
	Slope %/sec	.63	1.52	1.68	1.83
	Peak H/M ratio	.55	.55	.40	1.41
3	Time (ms)	61.80	39.80	52.70	33.10
	Slope %/sec	.59	1.10	.84	.93
	Peak H/M ratio	.48	.51	.51	.58
4	Time (ms)	121.40	62.80	80.50	73.40
	Slope %/sec	.25	1.19	.47	.75
	Peak H/M ratio	.66	1.05	.77	.79
5	Time (ms)	56.00	33.90	44.30	26.70
	Slope %/sec	1.11	2.04	1.32	2.50
	Peak H/M ratio	.85	.91	.82	.92
6	Time (ms)	89.00	26.80	90.70	73.40
	Slope %/sec	.56	2.10	.39	.61
	Peak H/M ratio	1.19	1.54	.46	.54
7	Time (ms)	55.50	25.50	34.00	34.20
	Slope %/sec	.09	.21	.46	.51
	Peak H/M ratio	.21	.20	.24	.25
8	Time (ms)	70.00	56.00	68.90	39.00
	Slope %/sec	.33	.66	.64	1.23
	Peak H/M ratio	.42	.42	.85	.85
9	Time (ms)	34.00	30.00	40.20	22.10
	Slope %/sec	1.07	1.44	.50	.61
	Peak H/M ratio	.60	.61	.73	.80
10	Time (ms)	61.00	58.00	37.00	31.00
	Slope %/sec	.17	.23	.67	.77
	Peak H/M ratio	.70	.72	.64	.67
11	Time (ms)	38.20	33.57	57.00	48.00
	Slope %/sec	1.31	1.93	.12	.61
	Peak H/M ratio	.66	.80	1.07	1.09

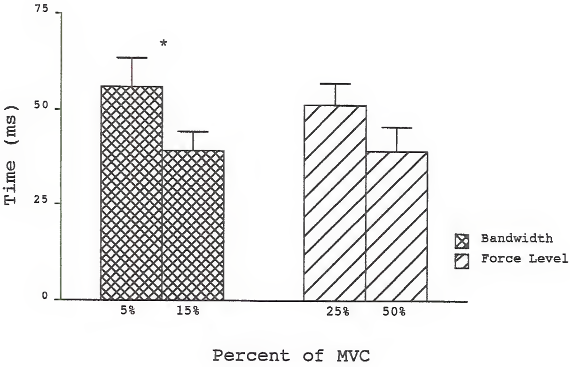


Figure 4-16. Mean (±SEM) data for the time of premovement facilitation for main effects of Bandwidth and Force. * $p \leq 0.05$.

(M = 56 ms) when compared to the 15% bandwidth (M = 39 ms). It appears that participants increased the time of facilitation for the 5% target. The time of facilitation, for a typical participant, for the 25% force level is shown in Figure 4-14. This figure displays that the time of facilitation for the 5% bandwidth was 56 ms, while the time for the 15% target was 33.9 ms. The time of facilitation, for this same participant, for the 50% force level is shown in Figure 4-15. Here the time of facilitation for the 5% bandwidth was 44.3 ms, while the 15% bandwidths time was 27 ms. These figures clearly show the change in the time of increased spinal excitability was shorter for the larger bandwidth.

However, the level of force did not affect the time of facilitation. Mean data established the time of facilitation for the 25% force level was 51 ms, while the 50% force level was 44 ms (see Figure 4-16). This appears to suggest, as did some of the kinetic variables, that when the force level was changed participants held time invariant.

Slope of Facilitation

The results for slope of premovement facilitation were identical to time of facilitation. The slope of facilitation was measured as the rate of change (or percent change) of the H/M ratio per second. There was a Bandwidth main effect ($F_{1,10}$

= 25.4, $p \leq 0.01$). Mean data established that the slope of facilitation was 7.4 percent/sec for the 5% bandwidth, while the slope of facilitation was 12.7 percent/sec for the 15% bandwidth (see Figure 4-17). A typical participant's slope of facilitation for the 25% force level is shown in Figure 4-14. This figure illustrates that the slope of facilitation for the 5% bandwidth was 10.5 percent/sec, while the slope for the 15% target was percent/sec. The slope of facilitation for the 50% force level, shown in Figure 4-15 ascertained that the slope of facilitation for the 5% bandwidth was 14.2 percent/sec, while the slope for the 15% bandwidth was 26.2 percent/sec. These figures showed a greater rise of facilitation for the larger bandwidth.

Additionally, force did not appear to influence the slope of facilitation. Mean data revealed that the slope of facilitation for the 25% force level was 9.3 percent/sec, while the 50% force level was 10.8 percent/sec. This data clearly showed that force played no role in determining the slope of facilitation.

Peak Facilitation

The results for peak facilitation were identical to time and slope of facilitation. Peak facilitation was defined as the value of the H/M ratio that occurred at the onset of EMG activity. For peak facilitation at the onset of soleus EMG

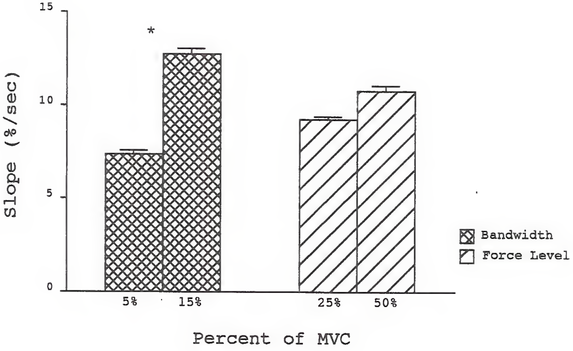


Figure 4-17. Mean (±SEM) data for the slope of premovement facilitation for main effects of Bandwidth and Force.
* $p \le 0.05$.

activity there was a Bandwidth main effect ($F_{1,10} = 8.6$, $p < 0.01$). Since all participants started at the same baseline level of motor neuron pool excitability, the difference in peak facilitation between bandwidths indicated that larger bandwidth generated a greater amount of spinal facilitation. Figure 4-18 shows that the mean response for the peak H/M ratio was .669 for the 5% bandwidth, while the peak H/M ratio for the 15% bandwidth was .758 H/M ratio. At peak facilitation of the motor neuron pool approximately 66% of M-max was active for the 5% bandwidth, while 75.8% of M-max was active for the 15% bandwidth. A typical participant's peak facilitation for the 25% force level is shown in Figure 4-14. This figure illustrates that peak facilitation for the 5% bandwidth was .853 H/M ratio, while the peak for the 15% target was .904 H/M ratio. Peak facilitation for the 50% force level, shown in Figure 4-15 ascertained that peak facilitation for the 5% bandwidth was .824 H/M ratio, while the peak for the 15% bandwidth was .916 H/M ratio. These figures clearly show a greater peak facilitation for the larger bandwidth.

The peak level of facilitation did not appear to be influenced by the level of force. Mean data revealed that peak facilitation for the 25% force level was .70 H/M ratio, while the 50% force level was .71 H/M ratio.

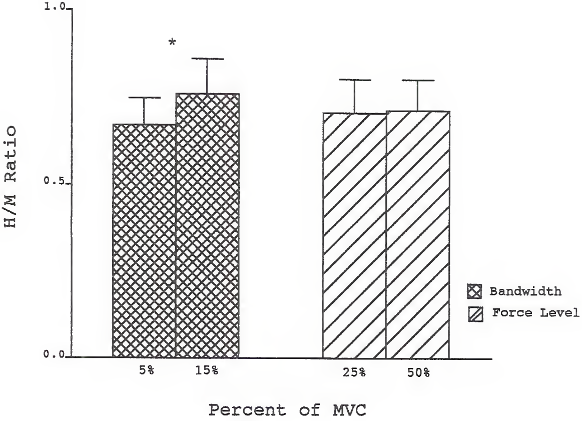


Figure 4-18. Mean (±SEM) data for the peak of premovement facilitation for main effects of Bandwidth and Force. * $p \leq 0.05$.

Summary of Results

Hypothesis # 1, was tested by measuring changes in the H-reflex prior to onset of EMG activity when the same level of a MVC was used to reach different target bandwidths. According to the hypothesis, time of premovement facilitation should be the same for both bandwidths, while peak facilitation should be larger for the 15% bandwidth. Additionally, the 15% bandwidth should provide a greater slope of premovement facilitation. The Bandwidth main effects for slope and peak facilitation supported the research hypothesis. However, the research hypothesis was not fully supported by the finding of a longer duration of premovement facilitation for the 5% bandwidth.

Hypothesis # 2, was tested by measuring changes in the H-reflex prior to onset of EMG activity when different levels of a MVC were used to reach the same target bandwidth. According to this hypothesis, time of H-reflex facilitation should be shorter for the 25% force level, while the peak and slope of H-reflex facilitation should be larger for the 50% force level. The results of this study did not support this research hypothesis. Contrary to the hypothesis, there were no differences between the time of facilitation, slope, and peak of H-reflex facilitation between the force levels.

CHAPTER 5
DISCUSSION, SUMMARY, CONCLUSIONS, AND IMPLICATIONS FOR FUTURE RESEARCH

This study was designed to systematically analyze how movement trajectories, EMG parameters, and the excitation pulse change as a consequence of manipulation of force level and accuracy in an isometric contraction. The duel-strategy hypothesis was used to initially establish the bandwidth and force levels for this study. However, since this study only evaluated two levels of force and bandwidth, the terms speed sensitive and speed insensitive strategies were dropped from the discussion. That is, a determination of different strategies of movement could not be made since only two levels of the factor were evaluated.

Isometric contractions of the soleus, were evaluated to 5% and 15% bandwidths at force levels of 25% and 50% of a subject's MVC. The excitation pulse was evaluated by measuring changes in soleus motor neuron pool reflex excitability prior to the specified contractions. The data from both studies (Study 1 and 2) will be synthesized along with resolutions of the experimental hypotheses. These findings and conclusions will be discussed within the framework of movement control and further areas of related future research will be evaluated.

Effect of Bandwidth Changes on Movement Trajectories and EMG Parameters

In the present study, subjects moved to a 5% and 15% bandwidth at force levels of 25% and 50% of a subject's MVC. When the data were collapsed across force level, the time to peak dF/dt and the time to peak force both increased with the smaller bandwidth. The results identified a difference in movement trajectories when going from the 5% to the 15% bandwidth. It appeared that subjects increased components of time when moving to the smaller bandwidth, in order to be accurate and comply with the instruction to be "fast and accurate". Similar results were established for the slope to peak dF/dt, the initial slope of force, and the slope to peak force. Subjects decreased the rate of rise of force with a corresponding decrease in bandwidth. This finding supports the assumption that subjects modulated both temporal and slope variables with changes in target accuracy.

Gottlieb, Corcos, and Agarwal (1989a) concluded that the initial rate of recruitment and the firing rates of the alpha motoneurons were adjusted through changes in the initial slope of soleus EMG activity and area of the agonist burst when the task focused on timing. Additionally, the myoelectric variables of Q_{30} and Q_{acc} were shown to both positively rise with increased peak torque (Gottlieb, Corcos, & Agarwal; 1989a; Gottlieb, Chen, & Corcos, 1995). In the present study, both variables were shown to positively increase with the larger bandwidth. Therefore, both Q_{30} and Q_{acc} were also sensitive to changes in bandwidth, and therefore movement accuracy.

Effect of Force Changes on Movement Trajectories and EMG Parameters

Corcos et al. (1990) suggested that various distances of movement could be equated with different levels of an MVC in an isometric task. In the present study, when the data were collapsed across bandwidth, the variables of time to peak dF/dt, both the initial slope and full slope to peak force, and the peak of dF/dt all increased to the larger force level. Even though no difference was established for slope to peak dF/dt for bandwidth, this lack of difference appeared to be due to a large standard deviation. That is, for the slope to peak dF/dt the difference between force levels was greater than the difference ascertained between bandwidths, where a significant main effect was established. A difference between slope to peak dF/dt and changes in force level have been previously established (Monohar, Brunt, & Robichaud, Manuscript in Review). The time to peak force was shown not to change with force level, which was identical to the results in the Monohar et al. study (Manuscript in Review). These finding denote that subjects increased both the time and slope to peak dF/dt in order to reach the specified force level within relatively the same period of time. Freud and Budingen (1948) supported these results by establishing different slopes for eight isometric force levels, when target accuracy was not changed. Additionally, Corcos et al. (1990) reported in their isometric study that subjects used different slopes of movement for four different MVC's to a 9% target. In the same paradigm, Corcos et al. (1990) established that when subjects were instructed to move at a comfortable pace, again subjects moved along different force trajectories. However, when these same subjects performed the same movements "as fast as possible" they tended to produce a mixture of force trajectories. In the present study, individual examination of the data revealed that the slope to peak dF/dt appeared unchanged for three subjects, while the remaining eight subjects had different slopes to peak dF/dt. This finding was essentially the same for individual data for the slope to peak force. This clearly indicated the importance of instruction and accuracy or perhaps the subjects pre-determined strategy, in determining the movement trajectories.

According to Gottlieb, Corcos, and Agarwal (1989a), the initial rate of recruitment and the firing rates of the alpha motoneurons were not adjusted with changes in the initial slope of soleus EMG activity, while changes were noted in the area of the agonist burst when accuracy was kept constant between the force levels. Additionally, the myoelectric variable of Q_{30} was also shown to be invariant while Q_{acc} increased positively with increased peak torque (Gottlieb, Chen, & Corcos, 1995; Gottlieb, Corcos, & Agarwal; 1989a). In the present study Q_{30} was also shown to be invariant, while Q_{acc} positively increased with the larger force level.

In this paradigm, when bandwidth was collapsed across force, the change in force level could have independently influenced some of the dependent variables. Gordon and Ghez (1984a) ascertained that the agonist burst was the programmed aspect of the movement and that for an isometric pulse this burst ended at peak dF/dt, which was equivalent to the measure of Q_{acc}. Therefore, components of the movement, such as slope, time to peak force or peak force, may have been influenced by other factors, such as onset, strength or duration of the antagonist muscle. The level of force has been shown to influence EMG burst duration and amplitude (Hoffman & Strick, 1993). In an isotonic wrist flexion task, a short-duration agonist burst pattern was established when low levels of force were produced as subjects moved short distances or with no external load. This was opposed to movements over longer distances or with an external load, where longer duration agonist bursts were noted. Thus, as the amount of force produced increased, subjects moved from increasing the magnitude to lengthening the duration of the agonist burst (Hoffman & Strick, 1993).

Neural Excitation Pulse

The dual-strategy hypothesis was based on the regulation of the net presynaptic input on the alpha motor neurons of the agonist and antagonist muscles, with the control signal being modeled as a rectangular excitation pulse, whose origin was not delineated (Corcos, Jaric, Agarwall, & Gottlieb, 1993; Gottlieb, Corcos, Agarwall, & Lattash, 1990). These "excitation pulses" were proposed to affect the agonist EMG burst duration or intensity which would correspondingly modulate the specific kinetic or kinematic goal. This "excitation pulse" was assumed to reflect the build-up pattern of motor neuron pool excitability prior to a voluntary movement. The build up pattern of spinal excitability can be referred to as "premovement facilitation" and may be dependent upon the type of movement. For example, in an anticipation timing task, Frank (1986) elicited an increase in premovement facilitation, when compared to a ballistic task. Additionally, shorter reaction times have been associated with a greater amount of premovement facilitation which began 70 ms prior to EMG onset (Eichenberger & Ruegg, 1984).

Since Eichenberger and Ruegg (1984) were unable to develop a relationship between force level and premovement facilitation, they suggested that different patterns of premovement facilitation may reflect the use of different movement strategies to perform the tasks. There has been no attempt to demonstrate the relationship of this “excitation pulse” to motor programming, when controlling both changes in both force level and accuracy. The present study established clear changes in premovement facilitation which corresponded with different levels of force and accuracy of an isometric contraction.

Movement Accuracy

Changes in premovement facilitation may relate to movement accuracy, which was evaluated at bandwidths of 5% and 15% of the specified force level. When the data was collapsed across force levels while manipulating movement accuracy, a decrease of 12% in peak facilitation and 40% in the slope of premovement facilitation was established for the 5% bandwidth. Additionally, the duration of premovement facilitation increased by 30% for the 5% bandwidth. It appears that the nervous system adjusted to slower movements at the smaller bandwidth by decreasing the rate of rise of premovement facilitation in order to comply with the instruction to be “fast and accurate”. Since the largest change occurred in slope of premovement facilitation, this finding concurs with Gottlieb et al. (1989a), who suggested that subjects modulate the rate of rise of the excitation pulse in an accurate task.

Force Level

Changes in motor neuron pool excitability have been suggested to relate to movement force (Frank, 1986). The data was collapsed across bandwidth, while manipulating the level of force. Force levels were evaluated at 25% and 50% of an MVC. No difference in the slope, duration, or peak level of premovement facilitation between the two force levels was established. The results for peak level of premovement facilitation was contrary to Butler, Yue, and Darling (1993), who reported that the amplitude of the H-reflex rose linearly with increased force output up to 60% of an MVC. The difference in this study was probably due to the type of task involved. In the Butler et al. (1993) study, the H-reflex was obtained during sustained isometric contractions at varying levels of an MVC. Additionally, there was no attempt to control movement accuracy, which the present study showed could influence the excitation pulse. In the present study, movement accuracy was controlled along with analyzing the H-reflex before EMG onset. Therefore, differences in the design of between these studies could account for the differing results.

Task Parameters

Several researchers have tried to establish relationships between reflex excitability and movement parameters such as premotor time, reaction time, and force (Brunt & Robichaud, 1996; Eichenberger & Ruegg, 1994; Frank, 1986). Past literature has indicated only moderate to poor correlations between premovement facilitation and premotor time, reaction time, and force. Eichenberger and Ruegg (1984) established that shorter premotor times and therefore reaction times were associated with a larger amount of facilitation, steeper slope of facilitation and shorter duration of facilitation, which was suggested might be due to different movement strategies. Even though this was not a reaction time study, short movement times indicated the tasks were ballistic. Findings similar to Eichenberger & Ruegg (1984) were noted, where shorter times to peak force for the larger bandwidth corresponded with a shorter duration and greater peak and slope of premovement facilitation.

This study was designed to try to reconcile the relationships between premovement facilitation and different isometric contractions. The main difference between force level and bandwidth appeared to be with the EMG variable of Q_{30}. Gottlieb et al. (1989b) used changes in Q_{30} as a means of estimating the slope of the rising phase of EMG activity, since this measure was relatively insensitive to EMG variability. They further suggested that as the time period for Q_{30} increased, then Q_{30} progressively began to look like Q_{acc}. The measures Q_{30} and Q_{acc} have been used to relate EMG activity to both movement parameters and the excitation pulse, with the "excitation pulse" proposed to directly affect the initial 30 to 40 ms of agonist EMG activity (Corcos et al., 1990). Gottlieb et al. (1989a) suggested that Q_{30} was a more sensitive measure for task changes than was Q_{acc}. Further, Q_{30} was suggested to be sensitive enough to establish differences in the slope of the EMG when movements had brief excitation pulses (Gottlieb et al., 1989b).

There was no difference for force levels in any of the three measures of premovement facilitation (slope, time and peak of facilitation). Since Q_{30} was invariant and Q_{acc} increased with force, it appeared that the invariance with Q_{30} may correspond with premovement facilitation. The results were different when evaluating movement accuracy. In this case, both Q_{acc} and Q_{30} positively increased with the larger bandwidth. Additionally, all three measures of premovement facilitation (slope, time, and peak of facilitation) where shown to significantly change with bandwidth. That is, the duration decreased, while the slope and peak increased with the larger bandwidth. With bandwidth changes, both Q_{acc} and Q_{30} appeared to correspond with changes in premovement facilitation.

Table 5-1 illustrates the mean data for bandwidth and force level. An analysis of this data reveals that for bandwidth and force level the pattern of change for Q_{acc} was identical with the pattern for the slope and peak of dF/dt (see Table 5-1). This finding corresponds with Gordon and Ghez (1984a), who established that the agonist burst (Q_{acc}) was highly correlated with the first time derivative of force (dF/dt). There was also no evident pattern between Q_{acc} and the parameters of premovement facilitation. Contrary, the pattern was different between bandwidth and force level and Q_{30}. In this case, it appeared that Q_{30} related to slope and peak of premovement facilitation. This finding is depicted in Table 1, where the order of change (low to high) for Q_{30} mimics that of slope and peak of premovement facilitation. This finding concurs with Gottlieb et al. (1989b), who asserted that only the first 30 ms of EMG activity would be task dependent. When these results were combined, it appeared that Q_{30} was able to distinguish between changes in force level and accuracy of the movement. Additionally, Q_{30} and the excitation pulse appeared to relate with the very initial aspects of the movement, while also being sensitive to changes in task variables.

Table 5-1

Mean Data for the Main Effects for Bandwidth and Force Level for Premovement Facilitation, Soleus EMG activity, and the First Time Derivative of Force (dF/dt).

Premovement Facilitation	**Bandwidth**		**Force Level**	
	5%	**15%**	**25%**	**50%**
Time (ms)*	56.00	39.00	51.00	44.00
Slope %/sec*	7.40	12.70	9.30	10.80
Peak H/M ratio*	.67	.76	.70	.71

Soleus EMG Activity	**Bandwidth**		**Force Level**	
	5%	**15%**	**25%**	**50%**
Q30 (%MVC)*	14.2	18.0	15.3	16.8
Qacc (%MVC)^	16.5	21.0	16.0	21.5

First Time Derivative of Force (df/dt)	**Bandwidth**		**Force Level**	
	5%	**15%**	**25%**	**50%**
Time (ms)*+	70.0	63.0	55.0	77.0
Slope %/sec*#	2.4	3.1	2.4	3.2
Peak dF/dt*+	1260.0	1492.0	1084.0	1670.0

* $p \leq 0.05$ for Bandwidth
+ $p \leq 0.05$ for Force Level
# $p \leq 0.06$ for Force Level
^ $p \leq 0.05$ for Bandwidth X Force Level Interaction

Models of Programmed Movement and Neural Control

Pulse-Height Vs. Pulse-Width Control

Voluntary ballistic movements are planned and programmed in advance (Brooks, 1986). Programmed movements can be evaluated by discerning which variables were regulated (remain invariant) and controlled (allowed to vary). Corcos et al. (1990) evaluated the variables of time and rate of rise of torque to explain programmed movement. Different variable combinations can support either a pulse-width or pulse-height model of motor control (Corcos et al., 1990). This support is dependent upon which variables are regulated (remain invariant) versus controlled (allowed to vary). In pulse-height control, either time to peak force or peak force is regulated, while the rate of rise of force is the controlled variable (Corcos et al., 1990). In the current study when analyzing across the bandwidths (5% and 15%), there was a significant difference in both the time and slope to peak force. These results did not concur with pulse-height control. However, the agonist burst for an isometric pulse has been ascertained to end at peak dF/dt, therefore the initial response measures may be more appropriate to analyze in the pulse-height control model (Gordon & Ghez, 1984). When bandwidths were collapsed across force levels, there was a 29% increase in the slope to peak dF/dt, while the time to peak dF/dt decreased by only 8% (5 ms) when moving from the 5% to the 15% bandwidth. That is, when moving to the larger target subjects increased the rate of rise of force while only modestly decreasing the time to peak dF/dt. Additionally, Gordon and Ghez (1987) ascertained a pulse-height model even when the time to peak force varied by up to 50 ms. Therefore, it appears from this data that the rate of rise of dF/dt was controlled while the time to peak dF/dt was regulated.

Corcos et al. (1990) proposed that pulse-height modulation of motoneuron pool would be achieved by varying the intensity of the "excitation pulses". In pulse-height modulation, the "excitation pulse" would be adjusted by either altering the pulse's amplitude or slope, while pulse duration may remain unchanged or it may change in the same or opposite direction as the amplitude (Gottlieb, et al., 1989a). Premovement facilitation was evaluated when the data was collapsed across force level and the subjects were trying to reach the 5% and 15% target bandwidths. This task focused on accuracy, not timing of the movement, and therefore, according to the dual-strategy hypothesis pulse-height modulation should be evident between these bandwidths. As predicted, the excitation pulse's amplitude increased by 12%, slope increased by 40%, while the duration decreased by 30% for the 15% bandwidth. This supported pulse-height control.

There is previous H-reflex literature which partially supports pulse-height control. Eichenberger and Ruegg (1984) established that shorter reaction times had a greater amount and shorter duration of premovement facilitation. These findings suggest that amplitude of premovement facilitation was modulated in this task. Again this finding, along with the findings from the current study support pulse-height control for movements that focus on accuracy.

Corcos et al. (1990) stated that movement to different force levels would be synonymous to moving to different distances and should exhibit pulse-width control where the rate of rise of force is regulated, while the time to peak force is controlled. When an annuluses was run across the force levels (25% and 50%), there was a main effect for the slope to peak force, while there was no difference for time to peak force. These results did not concur with pulse-width control. Again, when the initial components of the movement were analyzed, there was a 28% increase in the slope of peak dF/dt, while a 28.5% increase was noted in the time to peak dF/dt. These results indicated that both the rate of rise of force and the time to peak dF/dt proportionally increased with the increased force level. Hoffman and Strick (1993) reported that the level of force influenced whether subjects produced a pulse-height or pulse-width modulation of the agonist burst. Subjects were shown to move from pulse-height to a pulse-width modulation of the EMG burst as the amount of force was increased (Hoffman & Strick, 1993). The same type of results were produced when subjects performed movements over four different distances where peak EMG amplitude, area, and duration of the agonist burst increased with distance (Mustard & Lee, 1987). Additionally, Gordon and Ghez (1984) showed that the magnitude of agonist burst varied principally with peak force in both fast and accurate conditions. The proportional changes that occurred between changes in force level, time to peak dF/dt and slope of dF/dt indicated that the subjects adopted pulse-height control.

Ballistic and step tasks, where speed or timing and not accuracy were the dominate feature, have been shown to exhibit pulse-width control of the excitation pulse (Eichenberger & Ruegg, 1984). This would be achieved by modulating the pulse's duration, while the pulse's rate of rise should remain constant. Premovement facilitation was analyzed when different levels of an MVC were used to reach the 5% and 15% target bandwidths. In this task, speed or force was the dominate feature of the task. Contrary to the hypothesis, there was no change in the time or slope of facilitation between the force levels. However, the lack of significance for peak amplitude did support the hypothesis. Force level appears not to effect spinal facilitation. Therefore, the results of the current study did not support this research hypothesis.

There is some support in the literature for pulse-width control of the excitation pulse. Kagamihara and colleagues (1990) evaluated the time course of premovement facilitation in a ramp plantar flexion task. In the ramp task, the subject moved at a preselected cursor speed. The onset of spinal facilitation occurred at 92 ms prior to EMG onset during the ramp task. Additionally, during an anticipation timing task there was a lengthening of the time period of spinal cord facilitation (70 ms prior to EMG onset) (Frank, 1986). The dual-strategy hypothesis proposed that the excitation pulse in an anticipation timing or ramp tasks should mimic pulse-width control because timing and not accuracy was the dominate aspect of these tasks. Therefore, both of these examples appear to support the aspect for increased timing in pulse-width control.

Fragmentation of Premotor Time

The period of premovement facilitation implies the readiness of the central nervous system to implement the planned motor action (Brooks, 1986; Frank, 1986). If the excitation pulse reflects premovement facilitation, then changes in this period should correspond to changes in task or instructional variables. Premovement facilitation has been used to fragment premotor time into two separate intervals (Eichenberger & Ruegg, 1984). This division may allow one to determine whether a change in programming or movement execution occurred (Eichenberger & Ruegg, 1984). The first interval (I_1), from the stimulus presentation until the onset of H-reflex facilitation was suggested to represent stimulus processing and response selection. The second interval (I_2), from H-reflex facilitation until onset of EMG activity may reflect preparation of the motor system prior to movement execution. There is evidence which supports Eichenberger and Ruegg's (1984) division of premotor time.

Since this was not a reaction time task, the I_1 period could not be measured. However, due to the movement times, this task still would be considered ballistic. In the current study, an elongation of the I_2 period of premotor time for the smaller bandwidth was established. This supports Eichenberger and Ruegg's (1984) division of premotor time since a smaller bandwidth would require more execution time. Additionally, force level did not affect the duration of the I_2 period. This finding also supports that the I_2 period represents movement execution. Kagamihara and colleagues (1992) findings support the division of premotor time. Differences in premovement facilitation was evaluated between matched ramp and step/ballistic movements. A longer duration of premovement facilitation was established for the matched ramp movements. Since matched ramp movements would require more precision and thus a longer time to execute, these results would support the I_2 division of premotor time.

Ordering of H-reflex trials

Numerous studies have established the onset on premovement facilitation to occur between 55 ms and 80 ms prior to EMG onset in ballistic plantar flexion tasks (Eichenberger & Ruegg, 1984; Kots, 1977; Mitchie et al., 1976). However, varied interpretations of how to order trial data appears to have led to differing conclusions concerning the duration of premovement facilitation of the H-reflex. Despite the different methods of grouping the H-reflex data, the onset of reflex facilitation continually appeared to be time locked to the onset of EMG activity (Brunt & Robichaud, 1996; Eichenberger & Ruegg, 1984; Kots, 1977; Mitchie et al., 1976). The present study established time periods of increased facilitation from 39 ms to 56 ms for simple ballistic plantar flexion movements. These times are shorter than most previous studies.

The discrepancy in the duration of premovement facilitation appears to relate with differences in both the task and the method of analyzing the time period of premovement facilitation. Eichenberger and Ruegg (1984) and Frank (1986) analyzed the time of premovement facilitation by averaging the amplitude of baseline reflexes with those that reflected facilitation just prior to the onset of EMG activity. These researchers also grouped the H-reflexes into

25 ms time bins. This method of data analysis could overestimate the time of premovement facilitation by up to 25 ms. Manning and Hammond (1990) tried to rectify this problem by dividing the H-reflex data into 10 ms time bins. This method provided a more accurate measure of the duration of facilitation. Kagamihara and colleagues (1992) further improved on estimation of this time period by taking a running average over 5 consecutive trials.

One way to compare these different methods of analysis is to compare the number of data points that would be utilized if 30 data points within 75 ms of soleus EMG onset were acquired. If the data points were blocked into 25 ms time bins there would be three data points, while no more than five data points would be acquired if the data was blocked into 10 ms time bins. However, using a running average over five consecutive trials would result in 24 data points. From this perspective, the running average would give more data points, thereby enabling a more accurate estimation of the duration of facilitation. In the current study to ensure a more accurate representation of the time of facilitation, a running average over 10 trials was utilized. Some of the difference in the duration of facilitation between the current study and various other studies was most probably due to different methods of data analysis. Additionally, it was noted that as the method of analysis became more precise, the duration of facilitation for similar tasks, was shown to decrease.

Summary

The purpose of these experiments was to examine neural modulation to determine the existence of a neural excitation pulse during isometric contractions. The neural excitation pulse was evaluated through changes in spinal cord excitability prior to a voluntary contraction. These changes were analyzed by measuring changes in the soleus H/M ratio when subjects changed both force level and movement accuracy. The results supported the existence of different excitation pulses during the different movements. It appeared that changes in bandwidth were able to influence time, slope, and peak of premovement facilitation. However changes in the force level did not appear to affect premovement facilitation.

Conclusions

The conclusions for this series of experiments are specific to the question of neural control of single joint isometric contractions. Based on the findings of this study, the following conclusions are made:

1. When moving between the 5% and 15% bandwidths, the initial trajectories of movement (slope of dF/dt, and initial and full slope of force) all rise along different trajectories. This conclusion was consistent with findings where subjects were required to produce isotonic movements to different target widths (Gottlieb, Corcos, & Agarwall, 1989a, 1989b).

2. Subjects adopted a combination of movement trajectories (slope of dF/dt, and initial and full slope of force) when they moved to the same bandwidth at different force levels. Some subjects had movements which rose along the same trajectory, while others had movements that rose along different movement trajectories. This difference in movement trajectories between subjects was probably due to some_subjects adopting different movement strategies. This was consistent with Crocus's finding that when force levels were changed, that subjects' adopted an approximation of a pulse-width control policy (Corcos et al., 1990).

3. Different neural pulse patterns were present for the different movements. These differences were manifested by different changes in the slope, time, and peak of premovement facilitation, which may reflect different motor programs.

4. When the accuracy of the movement was increased, the neural pulse pattern was modified by increasing the

duration and lowering the slope and peak of premovement facilitation.

5. Changes in force level did not affect the neural pulse pattern. Therefore, it appeared that changes in force may not affect motor programming.

Implications For Future Research

On the basis of this study, the following suggestions are offered for future investigations concerning neural modulation of single and multi-joint movements:

1. This was the first study to investigate the existence of different neural pulses patterns, presumed to controlled single-joint isometric contractions in healthy subjects. An important area of future interest would be to investigate whether learning affects the neural pulse pattern.

2. The addition of more bandwidths may help to show how the nervous system adjusts between pulse-width and pulse-height modulation. The addition of more bandwidths would also allow for the analysis of different movement strategies.

3. An understanding of single-joint voluntary control is a prerequisite for studying unrestrained multi-joint movements. Therefore, this model may be expanded to multi-joint movements in the future.

4. Different patient populations may also be evaluated with this paradigm. The use of patient populations may help to discern the precise nature of dysfunction that produce cognitive, programming or execution deficits may be established. This may help to determine the most appropriate method for motor relearning and rehabilitation.

5. A recording from the motor cortex may be taken while subjects performed isometric contractions. This data could be compared with the premovement facilitation data to try to establish relationships between these parameters prior to an isometric contraction.

6. The anterior tibialis has been shown to be active during isometric contractions. It would be beneficial to establish the effect of the anterior tibialis influence on premovement facilitation. For example, is there a relationship between either the duration and/or magnitude of the anterior tibialis and the slope, time or peak of premovement facilitation .

Single-joint movements have specific organizing principles which guide an individual’s movement. This study addressed specific concerns over the neural control of single-joint isometric contractions in nondisabled individuals. However, the resolution of neural control in nondisabled individuals will lead to a clearer conceptual model with which to compare response from disabled individuals. This study also provided the groundwork for more sound recommendations for teaching motor skills. That is, since there was a difference between the spinal cord processing for accurate when compared with non-accurate movements there appeared to be a specificity for movements. This implied that movements should be taught within the content in which they are to be performed. Perhaps this study will provide the impetus for future research in this area to move in the appropriate direction for a more real world understanding of motor control.

APPENDIX A
INFORMED CONSENT FORM

Informed Consent to Participate in Research

The University of Florida
Health Science Center
Gainesville, Florida 32610

You are being invited to participate in a research study. This form is designed to provide you with information about this study. The Principal Investigator or representative will describe this study to you and answer any of your questions. If you have any questions or complaints about the informed consent process or the research study, please contact the Institutional Review Board (IRB), the committee that protects human subjects, at (352) 846-1494.

1. Name of Subject

2. Title of Research Study

Neural modulation of Voluntary Movements

3. a. Principal Investigator(s) and Telephone Number(s)

Julie Robichaud, MHS, PT, Graduate Student, Department of
Exercise and Sport Sciences, (352) 395-0085
Denis Brunt, Ed.D., P.T., Acting Chair and Associate Professor, Department of Physical Therapy, (352) 395-0085
Keith Tennant, Assistant Department Chair, Department of Exercise and Sport Sciences, 25 FLG, (352) 392-9575

b. Sponsor of the Study (if any)

American Physical Therapy Association - Education Division

4. The Purpose of the Research

A new model has been developed which explains how the nervous system controls movement. This model, known as the Duel-Strategy model, consists of two different methods for controlling movement. The H-reflex can be used as a measure of how the nervous system responds during movement. The purpose of this study is to determine if the nervous system responds differently when movements are performed using the two different methods.

5. **Procedures for this Research**

a. You will be asked to participate in two separate days of testing with each testing session lasting for approximately 2 hours. Testing will take place at the Physical Therapy School Laboratory of the University of Florida.

b. You will be seated with your back resting against the chair and your arms folded across your lap. You will have your right thigh secured to the chair by two straps and the your knee will be bent 60 degrees. Your right foot placed on a wooden surface with the ankle firmly stabilized by a belt so that no ankle movement can occur.

c. You will have surface skin sensors placed on the inside part of your calf. The skin under these sensors will be cleaned with alcohol before placement of the sensors. The sensors will be secured to your skin with adhesive electrode tape, foam cling wrap, and paper tape. The skin sensors will be used to measure the muscle activity in your lower leg.

d. A small electrical stimulation will be applied to the skin on the back of your knee. The nerve will be stimulated for a short time, at a rate of one every five seconds. The stimulus may feel uncomfortable at first, but you should adjust to the stimulus.

e. The initial testing will consist of finding the best location for the electrical stimulation. Once this location is found, the stimulation will be increased until a maximal muscle twitch response is observed. Once this level is determined, the stimulation will be turned down until a response that is about half of the maximal response is observed. This will be the amount of stimulation for the rest of the test.

f. You will be asked to push your foot down as if you were pressing down on a gas pedal. You will be asked to push down as hard as you can for 10 separate trials. The average of the 10 trials will be used to determine the maximum amount of force you are able to produce.

g. You will practice pushing your foot down with a specified amount of force, which will be determined from the average of the 10 maximum force trials. The specified force levels will correspond to 25% and 50% of the maximum amount of force you were able to produce.

h. You will be asked, following a light signal, to push your foot down to a specified force level. You will be asked to keep this force within a specified range, which will be 5% and 15% of the specified force level. For example, when pushing down with 25% force level, you may be asked to keep the force within a 5% range. In this example, you would be asked to maintain the force within 23.5% to 27.5% of your maximum force.

i. You will observe the specific force by viewing a computer screen, which will be placed at eye level, 20 inches in front of you. Lines will be drawn on the computer screen which will match the selected range of force. You will be able to see the amount of force you are pushing down with on the computer screen.

j. You will be tested under four different conditions. Conditions will consist of you pushing your foot down to a specified force level which will be 25% and 50% of the maximum amount of force you were able to produce. Each force level will be tested under two different ranges of force. The ranges will be 5% and 15% around the specified force output. In each condition, a small electrical stimulation will be applied at varying time periods following the light signal. A total of 100 trials will be performed for each tested condition.

6. Potential Health Risks or Discomforts

You may develop an area of redness where the stimulus was applied or underneath where the electrodes were placed. These areas of redness are common and usually last around one day. You may also develop (though rare) a rash that is red, hot, raised and itching, but this should not last for over five days. This is minimized by cleaning your skin before and after the study and by using hypo-allergenic tape and gel.

If you wish to discuss these or any other discomforts you may experience, you may call the Principal Investigator listed in #3 of this form.

7. Potential Health Benefits to You or to Others

This study provides no known benefit to you. The information gathered from this study will help investigators establish how the nervous system functions when you push your leg down to different targets.

8. Potential Financial Risks

There are no financial risks you.

9. Potential Financial Benefits to You or to Others

You will receive $10 when you complete the first day. You will receive $20 after the second day of the study.

10. Compensation for Research Related Injury

In the unlikely event of you sustaining a physical or psychological injury which is proximately caused by this study:

____ professional medical: or ____ professional dental; or __X__ professional consultative care received at the J. Hillis Miller Health Center will be provided without charge. However, hospital expenses will have to be paid by you or your insurance provider. You will not have to pay hospital expenses if you are being treated at the Veterans Administration Medical Center (VAMC) and sustain a physical injury during participation in VAMC-approved studies.

11. Conflict of Interest

There is no conflict of interest involved with this study beyond the professional benefit from academic publication or presentation of the risks.

12. Alternatives to Participating in this Research Study

You are free not to participate in this study. If you choose to participate, you are free to withdraw your consent and discontinue participation in this research study at any time without this decision affecting your medical care. If you have any question regarding your rights as a subject, you may phone the Institutional Review Board (IRB) office at (352) 846-1494.

There is no alternative procedure that would decrease the risk to you and allow the study to answer the questions.

13. Withdrawal From this Research Study

If you wish to stop your participation in this study for any reason, you should contact Julie Robichaud at 395- 0085. You may also contact the Institutional Review Board (IRB) Office at (352) 846-1494.

14. Confidentiality

The University of Florida and the Veterans Administration Medical Center will protect the confidentiality of your records to the extent provided by Law. You understand that the Study sponsor, Food and Drug Administration and the Institutional Review Board have the legal right to review your records.

15. Assent Procedure (if applicable): [Assent is the procedure used to obtain agreement to participate in the research from a subject, such as a child, who cannot give legal consent]

Assent procedures are not applicable to this study.

16. Signatures

____
(Subject's Name)

The Principal or Co-Principal Investigator or representative has explained the nature and purpose of the above-described procedure and the benefits and risks that are involved in this research protocol.

__________________________________ ____________________
Signature of Principal or Co-Principal Date
Investigator or representative obtaining consent

You have been informed of the above-descried procedure with its possible benefits and risks and you have received a copy of this description. You have given permission for your participation in this study.

__________________________________ ____________________
Signature of Subject or Representative Date

If you are not the subject, please print your name
____
and indicate one of the following:

______ The subject's parent
------- The subject's guardian
______ A surrogate
______ A durable power of attorney
______ A proxy
______ Other, please explain:

______________________________ _________
Signature of Witness Date

If a representative signs and if appropriate, the subject of this research should indicate assent by signing below.

___________________________ ________________
Subject's signature Date

APPENDIX B
IRB FORM

Institutional Review Board - 01 Protocol #

University of Florida Health Science Center (for IRB use only)

Project Cover Sheet

Project Title: Neural Modulation of Voluntary Movements

Name of Investigator: Julie Robichaud Title: Graduate Student

Department: Exercise and Sports Science College: Health and Human Performance

Box #: 100-154 Telephone # 395-0085

Fax #; Email Address:

Department Chair, Dissertation\Thesis Chair: (if applicable Keith Tennant

Co-Investigators:

Denis Brunt, Ed.D., PT
Julie Robichaud, MHS, PT

Please check all that apply:

X New Submission to the IRB

___ Resubmission:

___ Expedited (Must complete section #17)

___ Exempt (Must complete section #18)

___ Multi-center study

___ Training Grant

The undersigned accepts the responsibility to comply with Federal, State and Health Center policies relative to the protection of the rights and welfare of human subjects.

Signature of Principal Investigator (P.I.) Date

I approve this protocol for submission to the Institutional Review Board.

Chairperson or Director of Department Date

Introductory Questionnaire

1. Check all that apply:

___ Experimental\Marketed drug: IND #________

___ Experimental\Marketed drug: IND Exempt

___ Experimental\Marketed device: IND # ________

___ Experimental\Marketed device: IND Exempt

___ Investigator's Brochure submitted to IRB (one copy)

___ Sponsor's Protocol (1 copies)

___ Non-approved indication for approved drug

___ Non-approved dose for approved drug

___ Experimental surgical procedures

___ Radiation (i.e.: an x-ray study that is not part of the routine workup. Request for approval has or will be obtained from the Human use of Radioisotopes and Radiation Committee {HURRC}).

___ Radioactive Materials (Request for approval has or will be obtained from the Human use of Radioisotopes and Radiation Committee [HURRC]).

___ Deception of Subjects

___ Behavioral\Psychological research

___ Pharmacokinetic\Pharmacodynamic Research

_X_ Non-therapeutic Research

___ *Use of impaired subjects

___ Fetal research

___ Pregnant women

___ Children under 18 years of age

___ Exercise or Nutrition Study

___ Observation of disease progression

___ Use of Placebos

___ Prisoners

___ Other, please specify:

____
____

____
____

*Impaired subjects include those who have physical or mental limitations which restrict their ability to understand, or who are dependent on the individuals who may be consenting for them. The subjects include, but are not limited to people who are in one of the following categories: mentally or emotionally impaired, illiterate, prisoners, frail elderly, or those who require certain emergency care. Some are permanently impaired by definition of their circumstances; others are temporarily impaired.

2. The protocol that guides this research, originated:

___ at a sponsoring company/institution/agency.

___ from a grant proposal.

_X_ from the principal investigator.

___ other, please specify:

*Note that protocols and informed consent forms have to be adapted to the standards of the University of Florida, Health Center Investigational Review Board (IRB).

3. List all sources of financial and material support for this project:

(check column which applies)

Source of Funding	Funding Obtained	Applied for Funding
Drug/Device Manufacturer (please list):		
________	___	___
N.I.H.	___	___
C.R.C.	___	___
N.C.I.	___	___
Dept. or University	___	___
No Funding Required	___	___
Other: (please list) American Physical Therapy Association	X	___

4. Expected duration of the study: 1 year

5. Expected duration of the study for each individual subject: 120 minutes for two sessions

6. Subject Information:

a. Type of subjects to be studied (e.g., normal controls, patients with specific diseases)

Healthy Individuals

b. Estimated number of subjects at this site: __20__ other sites: __0__

c. Age range: __18 - 45 years__

d. Is selection of subjects based on gender: ___ Yes _X_ No (if Yes, complete the remainder of this question)

- _____ Males _____ Females

- Reason for selection:

  ___ Only the gender selected has the condition.

  ___ Other, please specify:

e. Is the selection of subjects based on a racial/ethnic basis? ___ Yes _X_ No
(if Yes, complete the remainder of the question)

- List which race(s) will be entered into the study.

- Reason for selection:

  ___ Only race(s) selected has the condition.

  ___ Other, please specify:

f. Will pregnancy test be required if individuals of child-bearing potential are to be included in the study?

_X_ Not Applicable ___ Yes ___ No (If no, please comment)

g. If subjects are pregnant, explain why it is essential to use these particular individuals:
_X_ Not Applicable

h. If subjects are children or impaired (as defined in the paragraph on the previous page), explain why it is essential to use these particular individuals:

Not Applicable

i. Describe any predominant relationship between the investigator(s) and the subjects in the study. Check all that apply:

___ teacher/student
___ health care provider/patient
_X_ friend/fellow student
_X_ researcher/subject
___ employer/cmployee
___ other (please explain):

7. **Compensation to Research Subjects:**

a. Monetary: _X_ Yes ___ No Amount: $ 30.00

b. Reimbursement of expenses: ___ Yes _X_ No

c. If there is to be monetary compensation, pro-rated payment is required. Please outline the amount and schedule of all payments. If a pro-rated payment scheme is not applicable, an explanation must be provided below.

1) Pro-rated payment scheme:
Subjects will be paid $10.00 for the first session and $20.00 for the second

2) No pro-rated payment, please explain:

Not Applicable

d. If study involves treating patients, will any of the drugs, devices, etc. be given to the patient free of charge? If so, please list.

Not Applicable

e. If appropriate, please comment on the following questions: Given the group of subjects you will recruit, could the monetary compensation unduly influence a subject to participate in this study or remain in this study when other factors in the subject's health/environment would keep the subject from doing so? If yes, please explain.

No

8. **Location of study:**

___ Shands Teaching Hospital
___ University of Florida Clinic
___ CRC inpatient
___ CRC outpatient
___ Cancer Center
___ Student Health Center
___ Dental Clinics
___ Center for Exercise Sciences
___ Hampton Oaks Clinic
_X_ Other: Physical Therapy School
___ Cancer Center
___ Park Avenue Clinics
___ V.A. Hospital, Inpatient
___ V.A. Hospital, Outpatient Clinic

9. **In the event of a medical emergency, plans for management are:**

___ On site physician with emergency medications and equipment.
_X_ Public or community emergency services (eg: 911)
___ Other (please explain):

10. **Funding of Research Protocol Procedures:**

a. Will any tests, surgical procedures, x-rays, etc., be performed which are additional to the routine work and/or therapeutic regimen for these types of patients?

___ Yes _X_ No

List:

b. Who or what agency will pay for the above tests?

Not Applicable

11. **What measures will be taken to protect the confidentiality of the information obtained?** (Specify what will be done with all tapes, pictures, and personal documentation of the subjects both during and at the completion of the research).

a. During the research: All subjects' data files will be coded to maintain confidentiality. The data recording forms and computer data disks will be locked and secured in a filing cabinet in the Physical Therapy Education Building.

b. After completion of the research: There will be no information reported from this study tat could identify an individual subject during presentations or publications. Data from the statistical analysis will be locked and secured in a filing cabinet in the Physical Therapy Education Building.

12. **Who will request the participation of the subjects in the study?** [Please note that if subjects will be placed at significant risk, informed consent must be obtained directly by the physician, chiropractor, podiatrist or dentist involved with the research.]

Principal Investigator: Julie Robichaud
Keith Tennant
Denis Brunt

13. **Informed consent will be obtained from (check all that apply):** (Refer to Investigators Manual page ___ for definitions)

_X_ The subject

______ The subject's parent

______ The subject's guardian

______ A surrogate

______ A durable power of attorney

______ A proxy

______ Other, please explain:

14. Is there an oversite committee which reviews safety data for this research study?

____ Yes __X__ No

If yes, please indicate what their specific role is, how often they meet, and how often they produce a report that can be shared with the IRB-01 office.

15. How will subjects be recruited for the study? (Submit a copy of any planned advertisement to be used for this protocol. Submit any future advertisements to the IRB prior to running the ad).

Subjects will be recruited through a verbal announcement during graduate and undergraduate courses in Physical therapy and Motor Control.

16. Conducting Research on the Clinical Research Center (Optional)

- ____ Y __X_ N Does your protocol involve timed blood sampling?
- ____ Y __X_ N Would you benefit from a facility to process and store blood samples?
- ____ Y _X__ N Would your protocol benefit from the use of an impatient or outpatient facility staffed by research-oriented nursing and dietary personnel?
- ____ Y _X__ N Does your protocol require controlled dietary intake and computerized nutrient analysis of diets?
- X___ Y ____ N Would you benefit from the use of a Data Services Lab to manage and analyze your research data, correspond electronically with colleagues throughout the world or access and analyze large public data bases?
- ____ Y __X_ N Would you be interested in speaking to a member of the Clinical Research Center (CRC) staff about conducting your research on the CRC?

17. Request for Expedited Status (If Applicable)

Research activities involving no more than minimal risk and in which the only involvement of human subjects will be one or more of the following categories (carried out through standard methods) may be reviewed by the Institutional Review Board through the expedited review procedure.

Please indicate under which category you are requesting expedited review for this protocol.

1. __ Collection of: hair and nail clippings, in a nondisfiguring manner. Deciduous teeth; and permanent teeth if patient care indicates a need for extraction.
2. __ Collection of excreta and external secretions including sweat, uncannulated saliva, placenta removed at delivery, and amniotic fluid at the time of rupture of the membrane prior to or during labor.

3. ___ Recording of data from subjects 18 years of age or older using noninvasive procedures routinely employed in clinical practice. This includes the use of physical sensors that are applied either to the surface of the body or at a distance and do not involve input of matter or significant amounts of energy into the subjects or an invasion of the subject's privacy. It also includes such procedures as weighing, testing sensory acuity, electrocardiography, electroencephalography, thermography, detection of naturally- occurring radioactivity, and electroretinography. It does not include exposure to electromagnetic radiation outside the visible range (for example, X-rays, microwaves).

4. ___ Collection of blood samples by venipuncture, in amounts not exceeding 450 milliliters in an eight-week period and no more often than two times per week, from subjects 18 years of age or older and who are in good health and not pregnant.

5. ___ Collection of both supra- and subgingival dental plaque and calculus, provided the procedure is not more invasive than routine prophylactic scaling of the teeth and the process is accomplished in accordance with accepted prophylactic techniques.

6. ___ Voice recordings made for research purpose such as investigations of speech defects.

7. ___ Moderate exercise by healthy volunteers.

8. ___ The study of existing data, documents, records, pathological specimens, or diagnostic specimens.

9. ___ Research on individual or group behavior or characteristics of individuals, such as studies of perception, cognition, game theory, or test development, where the investigator does not manipulate subjects' behavior and the research will not involve stress to subjects.

10. ___ Research on drugs or devices for which an investigational new drug exemption or an investigational device exemption is not required.

18. Request for Exempt Status (If Applicable)

Unless otherwise required by OPRR or the FDA, research in which the only involvement of human subjects will be in one or more of the following categories are exempt from IRB review.

Please indicate under which category you are requesting exempt status for this protocol.

1. ___ Research conducted in established or commonly accepted educational settings, involving normal educational practices

2. ___ Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey or interview procedures, or the observation of public behavior, so long as confidentiality is maintained. If all of the following are true, exempt status cannot be granted:

- Information obtained is recorded in such a manner that the subject can be identified, directly or through identifiers linked to the subject

- Subject's responses, if known outside the research could reasonably place the subject at risk of criminal or civil liability or be damaging to the subject's financial standing or employability or reputation. For example, the research deals with sensitive aspects of the subject's own behavior, such as illegal conduct, drug use, sexual behavior, or use of alcohol

3. ___ Research involving the use of educational tests, survey or interview procedures, or observation of public behavior that is not exempt under number 2 above, if the subjects are public officials or candidates for public office or a federal statute requires that the confidentiality of personally identifiable information will be maintained throughout the research and thereafter.

4. ___ Research involving the collection or study of existing data, documents, records, pathological specimens or diagnostic specimens, if these sources are publicly available or if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects

5. ___ Research and demonstration projects for public benefit.

6. ___ Taste and food quality evaluation and consumer acceptance studies.

***Note: Exempt Protocols for Pediatric Subjects:** According to Federal Regulations, exemption numbers 1,3,4,5,and 6 above are applicable to studies involving children. In number 2 above, the exemption regarding educational tests is applicable to research involving children. Research studying children and involving the observations of public behavior is exempt only if the investigator does not participate in the activities being observed.

Research utilizing survey or interview procedures with children must be receive full IRB-01 review.

A. Purpose of the Research for which you are requesting Exempt status:

B. Summary of Research Procedure:

Health Center
Institutional Review Board

1. PROJECT TITLE:

Neural modulation of Voluntary Movements

2. PRINCIPAL Investigator:

Julie Robichaud, MHS, PT, Graduate Student-
College of Health and Human Performance
Department of Exercise and Sport Sciences/
College of Health Professions
Department of Physical Therapy
Box 100-154, JHHSC
(352) 395-0085

Co-Investigators:

Denis Brunt, Ed.D., PT; Associate Professor
College of Health Related Professions
Department of Physical Therapy
Box 100-154; JHMHC (352) 395-0085

Keith Tennant, Ph.D.; Assistant Department Chair
College of Health and Human Performance
Department of Exercise and Sports Science
25 Florida Gym, (352) 395-0584

Mark Trimble, Ph.D., PT; Assistant Professor
College of Health Related Professions
Department of Physical Therapy
Box 100-154; JHMHC (352) 395-0085

3. ABSTRACT:

The analysis of movement dysfunction in patient populations is hindered because there is no comprehensive model that can analyze both programming and execution components of single-joint movements in healthy individuals. A model that encompassed both programming and execution components of movement would provide a more fundamental basis to the understanding of movement dysfunction. Until research can determine the precise nature of dysfunctions that produce cognitive, programming or execution deficits, then the most appropriate method of motor relearning or rehabilitation will be difficult to determine.

A recent model of single joint control, the dual-strategy hypothesis, has been developed by Gottlieb, Corcos and Agarwall (1989-A). This model divides movements into speed sensitive (SS) and speed insensitive (SI) strategies. The SS strategy is produced when the speed of the movement is implicitly or explicitly controlled. In the SI strategy there is no intention or requirement to control the movement speed. The same initial neural pulse is suggested to determine both force trajectories and electromyographic (EMG) activity. This neural pulse is suggested to be represented by changes in spinal cord excitability prior to movement onset, with the different strategies producing different neural impulse patterns. For example, the SS strategy is suggested to modulate neural pulse height, while the SI strategy may alter the neural pulse width.

Although Gottlieb and colleagues (1989-A) outlined specific relationships between torque trajectories and agonist activity with different movement strategies, there was no attempt to demonstrate the existence of the neural pulse or to show relationships between this pulse and motor programming. There is evidence which suggests different neural pulse patterns may reflect different patterns of movement. For example, in an anticipation timing task, Frank (1986) demonstrated a longer time period (70 ms) of increased spinal excitability prior to EMG activity. This would be classified as pulse width modulation. Additionally, in a ballistic plantar flexion task, Eichenberger and Ruegg (1984) ascertained that shorter reaction times had greater amounts of spinal facilitation, which would be classified as pulse-height control. Therefore, shorter reaction times may be carried out using a SS strategy, while longer reaction times may have defaulted to the SI strategy. The purpose of this study is to evaluate the neural pulse of movements performed under both SS and SI strategies. This will allow the evaluation of whether these strategies produce different neural pulses as measured by changes in spinal excitability prior to movement onset.

4. Specific Aims:

A) The dual-strategy hypothesis appears to provide a model for unifying principals for the control of isotonic single-joint movement. Isometric movements have been evaluated to determine if these movements are governed by the same principals of single-joint movement. The research on isometric movements did not fully support the existence of the dual-strategy model. This study will determine the relationship between EMG activity and torque trajectories during isometric contractions to determine if the dual-strategy model can be applied to these contractions. Isometric contractions will be performed to specified levels of force, which will be related to the maximum amount of force that was produced. The force level will be maintained within a specified range of force. For example, subjects may be asked to produce a force between 45% and 55% of their maximal force output. This would be defined as a 50% force level with a 10% range.

B) The dual-strategy hypothesis proposed that different strategies will produce different excitation pulses. This pulse, purposed to modulate spinal excitability, is suggested to be reflected by changes in the H-reflex. The H-reflex is a non-invasive test that can be used to measure changes in spinal cord excitability. The proposed neural mechanism (spinal excitability), that is suggested to govern the different strategies, will be evaluated.

5. Background and Significance:

There is no comprehensive model analyzing programming and execution components of movement. A recent model of single joint control, the dual-strategy hypothesis, has been recently developed (Gottlieb, Corcos & Agarwall, 1989-A). This model is based upon four propositions: 1) movements are planned according to strategies which are a set of rules among task and instructional variables (Gottlieb, Corcos & Agarwall, 1989-A), 2) the control of single-joint movements are based on at least two strategies which include the SI and SS strategy, 3) the choice between the strategies depends on implicit or explicit instructions of whether or not to control movement speed, and 4) the same initial neural pulse controls both force trajectories and EMG activity. The dual-strategy hypothesis can account for movements across different distances, inertial loads, different target widths and over different movement speeds (Gottlieb, Corcos & Agarwall, 1989-A, Gottlieb, Corcos & Agarwall, 1989-B; Corcos, Gottlieb & Agarwall, 1989). The SS and SI strategies are suggested to produce different neural pulses, which may be reflected by changes in spinal cord excitability prior to the onset of the movement. The dual-strategy model has been demonstrated for isotonic movements, however ambiguity exists whether isometric contractions can be classified by this model. This study will also analyze if the dual strategy model can be extended to isometric movements.

Gottlieb, Corcos, and Agarwall (1989-A) define the SI strategy as movements that are "insensitive" to the speed of the movement. Single-joint movements performed under this strategy demonstrated a linear relationship between peak accelerating torque and the measured variables of peak torque, peak velocity, and movement time. Additionally, when these variables are plotted against time, all initially rise along the same trajectory. These relationships still hold when task variables change such as distance moved or inertial load. For example, as distance decreases there is an linear decrease in peak velocity, peak torque and movement time (Gottlieb, Corcos & Agarwall, 1989-A,B).

The speed-sensitive strategy consists of movements where speed is implied either explicitly or implicitly. For example, subjects would be instructed to move in a given time period, to different sized targets at the same distance or to move as rapidly as possible. This strategy demonstrated that peak accelerating torques, and peak velocity all linearly increased with an increase in movement speed. However, these variables were shown to initially rise along different trajectories.

The relationships between peak accelerating torque and EMG activity appear to account for differences between instructional variables (Corcos, Gottlieb & Agarwall, 1989; Gottlieb, Corcos & Agarwall, 1989-B). Additionally, the excitation pulse, in addition to controlling limb motion, was suggested to modulate agonist EMG activity. To further analyze EMG activity, agonist activity was divided into two separate time periods. The first time period (Q30) consisted of the first 30 milliseconds of agonist activity. The agonist activity after the initial 30 milliseconds until the end of acceleration was described as Q acceleration (Qacc). Depending upon the movement strategy, these phases of EMG activity demonstrated different relationships with peak accelerating torque in isotonic movements.

In a SI strategy, the two phases of EMG activity were ascertained to have different relationships with peak accelerating torque. The variable, Q30, was shown to be insensitive to the distance moved or inertial load (task variables). That is Q30 did not appreciably change with the manipulation of movement distance or load (Gottlieb, Corcos & Agarwall, 1989-B). In contrast, Qacc demonstrated a linear relationship with changes in task variables (Gottlieb, Corcos & Agarwall, 1989-B).

The SS strategy showed that peak accelerating torque and both Q30 and Qacc increased linearly with an increase in movement speed. For example, in the SS strategy, as the speed of the movement increased there was a corresponding increase between peak accelerating torque and Qacc. This relationship was also established for Q30 under the SS strategy (Corcos, Gottlieb & Agarwall, 1989). Therefore, both Q30 and Qacc were sensitive to the speed of movement. Additionally, the onset of antagonist EMG activity was delayed with an increase in movement time (Corcos, Gottlieb & Agarwall, 1989).

The SS and SI movement strategies may be reflected by demonstrate different neural pulse patterns. These neural pulses are suggested to be the initial impulse that should be reflected by changes in motoneuron pool excitability prior to the onset of the movement (Gottlieb, Corcos & Agarwall, 1989-A). The level of motor neuron excitability has been investigated by the Hoffman (H-reflex) (Hugon, 1973, Schieppati, 1987). There appears to be support for different movement strategies being reflected by changes in spinal cord excitability prior to onset of EMG activity. For example, in an anticipation timing task, Frank

(1986) demonstrated a longer time period (70 ms) of increased spinal excitability prior to EMG onset. Additionally, Kagamihara and colleagues (1990) evaluated the time course of spinal facilitation in a ramp plantar flexion task. The ramp task demonstrated the onset of spinal facilitation at 92 ms prior to EMG onset. The dual-strategy hypothesis proposes that the excitation pulse in an anticipation timing or ramp tasks should be classified as a SI strategy because movement speed is not the dominate aspect of these tasks. Therefore, both of these examples appear to support pulse-width modulation of spinal cord excitability.

Since speed is the dominate feature of ballistic and step tasks, these tasks would be classified as SS according to the dual-strategy hypothesis and should demonstrate pulse height modulation. Numerous studies have demonstrated the onset on spinal facilitation occurred between 55 - 80 ms prior to EMG onset in ballistic plantar flexion tasks. Additionally, Kagamihara and colleagues (1990) evaluated the time course of spinal facilitation in a ballistic step task. The step task demonstrated spinal facilitation at 55 ms prior to EMG onset. These examples appear to demonstrate that the duration of increased spinal excitability is constant for ballistic movements, which would tend to support pulse-height modulation. However, there was no analysis of differences in the levels of spinal cord excitability. Additionally, there has been no analysis of differences between SS and SI strategies (e.g. pulse width or pulse height modulation) and modulation of spinal cord excitability. This study will analyze differences in spinal cord excitability during the performance of SS and SI tasks.

6. RESEARCH PLAN:

Subject Eligibility

Subjects will include healthy individuals (male or female) over the age of 18 years. All subjects will have normal or corrected-to-normal vision and will be asked to refrain from caffeine and alcohol 12 hours prior to the study (Eke-Okoro, 1982). Self disclosure will be utilized when determining if a subject meets criteria for selection.

Study Design

Subjects will be seated in a modified chair with leg and head rests. A device is attached to the chair that, regardless of leg length will maintain the subject's hip in 90 degrees of flexion, knee in 120 degrees of flexion and ankle at neutral (Hugon, 1973). The foot will be secured to a wooden board and under the metatarsal heads a force transducer will be positioned which measures torque produced during voluntary isometric plantar flexion. Output from the force transducer will be sampled in real time, on-line on a computer screen and recorded for further analysis. Torque will be monitored by the subject on a computer screen that will be positioned, at eye level, 20 inches in front of the subject. The Acknowledge software program will be utilized for data collection and analysis.

Soleus muscle EMG activity will be recorded with a surface electrode that will be placed on the dorsal medial surface of the posterior calf, inferior to the muscle belly of the gastroncnemius (Maryniak & Yaworski, 1987). Gastroncemius muscle activity will be recorded with surface electrodes placed over the muscle belly of the gastroncnemius. The recording electrode will consist of two silver-silver chloride electrodes 1 cm in diameter embedded in an epoxy-mounted preamplifier system (TU) (X35). A reference electrode will be attached on the anterior surface of the tibial crest.

H-reflexes will be elicited using an isolation unit attached to a Grass 44 stimulator. A ground electrode will be placed under the stimulated thigh. One ms stimulations will be applied to the skin over the tibial nerve in the popliteal fossa. Proper cathode placement will be determined when 1) the direct motor reflex (M-wave) and Hoffman reflex (H-wave) displays similar wave configurations 2) the H-reflex is evoked before the M-reflex 3) and the least amount of current is required to elicit a H-reflex. The stimulating intensity will be increased until a maximum M-reflex is observed, after which the average of three M-reflexes will be calculated. The intensity will be decreased until a 50% H-reflex is obtained while maintaining a small M-wave (Hugon, 1973). This will be the stimulating intensity for the experiment. The processed signal will be sampled on-line via an analog to digital converter (Biopac) at 1000 HZ for 500 ms.

Procedure

Following electrode application, the subject will be positioned in the chair with their back resting against the chair, arms folded across their lap and their head positioned on a head rest designed to eliminate head movement. The tested thigh will be secured to the chair by straps that will be placed over the medial and distal portions of the femur. The knee and ankle will positioned according to the constraints of the equipment.

Testing will began with learning trials to familiarize the subject with the testing procedure, task and equipment. Subjects will be instructed to perform 10 maximum isometric plantar flexion contractions. Pre-selected percents (25% and 50%) of the subject's maximum contraction will be calculated. Two target bandwidths (5% and 15%) of the pre-selected percent of a subject's maximum voluntary contraction will be calculated. Reference lines corresponding to the specified target bandwidths will be shown on the computer screen. For example: If you are asked to push down with a force that is 25% of the maximum voluntary contraction within a 10% range, reference lines would be indicated on the computer screen at the levels of 20% and 30% of the maximum voluntary contraction.

With concurrent feedback, subjects will practice matching isometric plantar flexion contractions to the specific force level. After 50 trials, feedback will be removed and the subject will be asked to complete 10 additional trials. If 80% of the trials match within a10% target bandwidth, the subject will be considered to have learned the task and testing will be initiated. During testing subjects will receive concurrent feedback.

Subjects will be instructed that following a light signal they are to produce an isometric contraction by plantar flexing their foot. A red light will be presented prior to task implementation. Subjects will perform isometric contractions to each specified force level (25% and 50% of the maximum voluntary contraction) and target bandwidths (5% and 15%). During these trials a stimulus will be used to elicit the H-reflex. The intervals between light and stimulus to elicit the H-reflex will consist of five intervals ranging from 30 to 150 ms prior to onset of EMG activity. The intervals within each trial block will be randomized. A variable fore period of between 8 and 10 seconds will be used between trials.

The specified force levels will be blocked, after which the target bandwidths will be randomized to determine presentation order to the subject. Prior to giving the red light, subjects will have to demonstrate no background EMG activity, which will be monitored on-line.

Data Analysis

The dependent measures will be fractionated reaction time ($I_1$and I_2) intervals, amplitude and slope of the H-reflex form the onset of EMG activity. Reaction time will be fractionated into two separate intervals. The first interval (I1) is from the stimulus onset until facilitation of the H-reflex. The second interval (I2) is from H-reflex facilitation until onset of EMG activity. The slope of rise and amplitude (peak to peak measurement) will be calculated for the H-reflex for both force level's bandwidths (5% and 15%). Independent measures will be the five stimulus intervals within each trial block, ten blocks of trials (average of ten measurements) over time and test conditions. A 2 X 2 X 5 (Force level X Bandwidth X stimulus intervals) completely repeated design ANOVA will be used to compare differences among the test conditions for each dependent measure. Additionally the dependent variables of peak torque, peak acceleration torque (acceleration of force). and EMG activity (Q30 and Qacc) will be analyzed using a 2 (50%

and 25% of maximum force) X 2 (5% and 15% bandwidths) repeated measures design. In this analysis stimulus intervals will not be an independent variable. Means contrasts will follow significant main effects. All level of significance will be designated at $p \leq 0.05$. A Super ANOVA statistical program will be used for data analysis.

7. Potential Health Risks:

Skin irritation may occur from the adhesive tape of the recording/stimulating electrodes or coupling gel. The incidence of this is minimized by cleaning the skin thoroughly before and after the experiment and using hypo-allergenic adhesive tape and gel. A skin inspection will be done prior to the application and after the removal of the electrodes. The electrodes will not be applied to irritated or broken skin.

There are two major contraindications when using electrical stimulation to record the H-reflex. They are cardiac pathology and thrombophlebitis. Electrical stimulation can cause further irregularity in a heartbeat when an arrhythmia exists or interfere with the normal function of a pacemaker. These risks are greatest when stimulating electrodes are placed on the upper extremity or over the thorax. The application of electrodes in this study are on the lower extremities. Evidence also suggest that using stimulation currents in the presence of thrombophlebitis can break off fragments which can be converted into an embolus.

Applying electrical stimulation to the tibial nerve may cause pain or discomfort to the subject. This is minimized by starting the stimulus at a low level and then slowly increasing the stimulus.

8. Potential Health Benefits:

This study provides no known benefit to the subjects, but the information gathered from this study will help investigators establish the nervous system mechanisms of responding to a visual stimulus at varying amounts of force. This will also allow the analysis of the existence of a neural pulse which is proposed to dictate two different strategies of movement.

9. Potential Financial Risks:

There are no foreseeable financial risks.

10. Potential Financial Benefits:

Subjects who complete the study will receive $30 in compensation. They will receive $10 after completion of the first half of the study and an additional $20 at the completion of the study.

11. Conflict of Interest:

There is no conflict of interest involved with this study beyond the professional benefit from academic publication or presentation of the results.

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BIOGRAPHICAL SKETCH

Julie Ann Robichaud was born on June 30, 1964, in Marysville, California. She graduated from Captain Shreve High School in 1982. She completed her undergraduate work at Centenary College in Shreveport, Louisiana, and Louisiana State University at Shreveport before pursuing a physical therapy degree. She attended Louisiana State University Medical Center and was awarded a Bachelor of Science in Physical Therapy in 1987. Following graduation she worked as a physical therapist at Schumpert Medical Center before returning to school. In 1990 she earned a Master of Health Science degree from the University of Florida. She returned to work as a physical therapist before enrolling at the University of Florida in the College of Health and Human Performance as a Ph.D. candidate in 1992. She completed her dissertation and was awarded the Ph.D. degree in August 1997.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

L. Keith Tennant, Chair
Associate Professor of
Exercise and Sport Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Denis Brunt

Denis Brunt, Cochair
Associate Professor of
Physical Therapy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Engineering.

Mark H. Trimble
Assistant Professor of
Physical Therapy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Robert N. Singer
Professor of Exercise and
Sport Sciences

This dissertation was submitted to the Graduate Faculty of the College of Health and Human Performance and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1997

Dean, College of Health and
Human Performance

Dean, Graduate School